Hidden in plain sight: searching for dark matter signals in the Galactic halo

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op dinsdag 11 oktober 2022, te 10.00 uur

door

Ariane Helena Dekker

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Publications

This thesis is based on the following publications:


   Presented in Chapter 2.

   AD wrote the sky-map simulations and analysis. All authors were involved in planning the project. MC provided the dark matter fluxes. The manuscript was drafted by AD and MC, with input from SA.


   Presented in Chapter 2.

   All authors were involved in planning the project and in writing the draft of the manuscript. AD and MC performed the model-independent bounds. SP, CA and AC performed the model-dependent bounds and compared with complementary constraints.


   Presented in Chapter 3.

   AD was responsible for planning the project with input from KN and SA. The manuscript was primarily written by AD with input from EP and FZ. All the authors provided input and feedback on the manuscript. EP and FZ performed the simulations and analysis for sterile neutrinos. AD performed the axion-like particle analysis.

Presented in Chapter 4.

AD wrote the warm dark matter subhalo model under supervision of SA. KN provided input for sterile neutrino properties. CC and SA provided input on the Milky-Way satellite observations and halo-galaxy connection. The draft was written by AD with input and feedback from all authors.

**OTHER PUBLICATIONS AND PREPRINTS BY THE AUTHOR:**


**CONFERENCE PROCEEDINGS BY THE AUTHOR:**


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Introduction

In the standard cosmological model, 85% of all the matter in the Universe consist of the elusive matter that is called dark matter. Observations from laboratory to astrophysical and cosmological scales have provided a wide range of information on dark matter properties such as the potential interactions, spatial distribution on the sky, and the total abundance. However, crucial questions around the nature of dark matter remain unanswered, as no conclusive detection has yet been made. Moreover, a future dark matter signal has to satisfy a range of observational constraints that depend on different underlying assumptions and uncertainties, challenging the search. Indeed, the dark matter mass, the interactions with nuclei, and the lifetime are only weakly constrained. Identifying dark matter will be one of the most important discoveries in particle physics and cosmology. Meanwhile, on the road to answering these questions, numerous new mysteries in the Universe have been revealed and solved, making it a rewarding field of research full of wonders.

In this thesis, we explore various dark matter properties by using astrophysical observations within the Galactic halo. In particular, in Chapter 2 we discuss indirect dark matter searches using high-energy neutrino data, where we set limits on the dark matter lifetime and interaction cross-section based on a non-detection. In Chapter 3, we use up-coming X-ray data to test the detectability of sterile neutrinos and axion-like particles, both well-motivated dark matter candidates. Finally in Chapter 4, we constrain the dark matter mass using the observed Milky Way satellite galaxies. We develop a model that predicts the amount of Milky Way satellite galaxies for a given dark matter model and we compare with the observed abundance. To introduce and motivate the research conducted, I discuss in this Chapter the standard cosmological model, dark matter evidences and potential dark matter candidates. Furthermore, I will discuss issues to the standard cosmological model and dark matter detection techniques.
1 Introduction

1.1 The $\Lambda$CDM Universe

In the standard cosmological model the Universe is assumed to be expanding, and to be spatially-flat, homogeneous and isotropic. Homogeneity and isotropy imply that the Universe looks the same in all directions from any point in space. Today it consists of the cosmological constant ($\sim 70\%$), cold dark matter ($\sim 25\%$) and baryons ($\sim 5\%$) and it is therefore known as the $\Lambda$CDM model. Baryonic matter consists of particles that are described in the Standard Model (SM), which I discuss in the following section.

The rate of expansion depends on the composition of Universe, which was different throughout time. For instance, right after the Big Bang, the Universe was hot and dense and most particles were consequently moving relativistically. Therefore, the energy in the Universe was mainly in the form of radiation. As the Universe expanded and cooled, relativistic particles became non-relativistic, and the Universe transitioned to a matter domination era. The expansion rate is described by the Hubble parameter $H^2(t) = \left(\frac{da}{dt}\right)^2 = H_0^2 \left(\Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_\Lambda\right)$, where $H_0 = 67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Aghanim et al. 2020) is the Hubble parameter today and $a$ is the dimensionless scale factor that describes the expansion. Moreover, $\Omega_i = \rho_i / \rho_c$ is the energy density of radiation ($i = r$), matter ($i = m$) and the cosmological constant ($i = \Lambda$) normalized by the critical density $\rho_c = 3H^2/8\pi G$. The critical density today is found to be $\rho_{c,0} = 2.8 \times 10^{11} h^2 \text{ M}_\odot \text{ Mpc}^{-3}$, with $h$ the dimensionless Hubble constant defined as $H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$, and the dimensionless energy densities are measured today as $\Omega_{r,0} = 0$, $\Omega_{m,0} = 0.3166 \pm 0.0084$ and $\Omega_{\Lambda,0} = 0.6834 \pm 0.0084$ (Aghanim et al. 2020). The relevant events in the history of the Universe will be described in this Chapter, and throughout my thesis I use natural units with $\hbar \equiv c \equiv 1$.

### Standard Model

The SM contains fermions (half-integer spin) and bosons (integer spin). Bosons mediate the forces and consist of the photon (electromagnetic force), the $W^\pm$ and $Z^0$ bosons (weak force), eight massless gluons (strong force) and the Higgs boson which generates mass to the massive SM particles through the Higgs mechanism (Englert & Brout 1964; Higgs 1964). Fermions can be further divided into two categories, quarks and leptons. Quarks interact with all forces and are the building blocks of matter, while leptons do not interact with the strong force. Moreover, between the leptons, there are 3 charged leptons ($e$, $\tau$, $\mu$) and 3 neutral leptons ($\nu_e$, $\nu_\tau$, $\nu_\mu$), where the latter ones only interact with the weak force and have no mass in the SM. Table 1.1 represents a summary of the particles in the SM with their corresponding masses obtained from Zyla et al. (2020).


### Fermions

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Bosons</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>d</td>
</tr>
<tr>
<td>(up, 2.16 MeV)</td>
<td>(down, 4.67 MeV)</td>
</tr>
<tr>
<td>c</td>
<td>s</td>
</tr>
<tr>
<td>(charm, 1.27 GeV)</td>
<td>(strange, 93 MeV)</td>
</tr>
<tr>
<td>t</td>
<td>b</td>
</tr>
<tr>
<td>(top, 172 GeV)</td>
<td>(bottom, 4.18 GeV)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Leptons</th>
<th>Bosons</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>νₑ</td>
</tr>
<tr>
<td>(electron, 0.511 MeV)</td>
<td>(electron neutrino)</td>
</tr>
<tr>
<td>μ</td>
<td>νμ</td>
</tr>
<tr>
<td>(muon, 105 MeV)</td>
<td>(muon neutrino)</td>
</tr>
<tr>
<td>τ</td>
<td>ντ</td>
</tr>
<tr>
<td>(tau, 1776 MeV)</td>
<td>(tau neutrino)</td>
</tr>
</tbody>
</table>

\[ T \approx t^{-1/2} \]

Table 1.1: Standard Model particles.

### History of the Universe

The history of the Universe after the Big Bang can be described as a function of the temperature \( T \), as it decreases with increasing time \( t \) as a consequence of the expansion of the Universe related by \( T \approx t^{-1/2} \). In the early Universe the SM particles were moving relativistically due to the high temperature, and as a result of frequent interactions with each other they were kept in thermal equilibrium in the ‘thermal bath’. The interaction rate is given by \( \Gamma \equiv n\sigma v \), with \( n \) the number density, \( \sigma \) the interaction cross-section and \( v \) the velocity of the particle, which is roughly 1 at early times. When the temperature drops below any particle’s mass, the creation of that particle and antiparticle becomes inefficient, and it starts to annihilate. When the interaction rate becomes smaller than the expansion rate \( (\Gamma \ll H) \) they leave the thermal bath and obtain the relic abundance as observed today.

When the temperature cooled to around 150 MeV, the quarks that were still in the thermal bath started to form baryons (mainly protons and neutrons) and mesons (mainly pions) through the strong force. This process is referred to as the quantum chromodynamics (QCD) phase transition. Soon after, around 1 MeV, neutrinos decouple from the thermal bath and produced the cosmic neutrino background. The cosmic neutrino background is yet to be observed directly, as it is challenging due to their very weak interactions. Dark matter could have been in the thermal bath and decoupled at a temperature depending on its mass. There are however models in which dark matter was never in thermal equilibrium and the observed dark matter abundance is produced through different processes in the early Universe. I discuss relevant thermal and non-thermal dark matter candidates and their production mecha-
anisms in Section 1.3.

Around 100 keV, *Big Bang Nucleosynthesis* (BBN) took place through a sequence of events in which light elements such as hydrogen, helium and lithium were formed through synthesis. The predicted BBN abundances of light elements have been confirmed by the observed abundances (Burles et al. 2001). Heavier elements such as carbon and oxygen were produced much later due to evolving and exploding stars. Much later, around 0.30 eV the temperature was low enough that atoms became stable. For instance, hydrogen was produced through $e^- + p^+ \rightarrow H + \gamma$, in which the energy of the photons was too low to scatter off the electron and the reverse reaction became inefficient. The strongest coupling between photons and the thermal bath was through Thomson scattering ($e^- + \gamma \rightarrow e^- + \gamma$), however, since the electron density dropped due to the formation of stable atoms, the photons decoupled from the thermal bath. This can be observed today as the *cosmic microwave background* (CMB), which was discovered in 1965 by Penzias & Wilson (1965) for which they received the Nobel prize. These photons show a nearly isotropic blackbody distribution with a mean temperature of 2.7 K. As the temperature is almost the same in all directions, it indicates that the photons were in thermal equilibrium. On large scales ($\gtrsim 100$ Mpc), the CMB proves that the radiation is homogeneous and isotropic, which has also been confirmed by various large scale structure observations (Clarkson & Maartens 2010; Coleman & Pietronero 1992; Hogg et al. 2005). On small scales, the COBE satellite was the first to find fluctuations of the order of $\sim 10^{-5}$ K (Smoot et al. 1992). The fluctuations on the sky can be assessed through the two-point correlation function given by $\langle \delta T (\hat{n}) \delta T (\hat{n}') \rangle$. Two-point correlation functions can provide important information on the underlying physics and have been assessed for various applications in cosmology and astroparticle physics, and I will therefore elaborate on the derivation. It is useful to expand the temperature fluctuations into spherical harmonics as

$$\delta T (\hat{n}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m} (\hat{n}),$$

where $a_{\ell m}$ are the expansion coefficients and $Y_{\ell m}$ the spherical harmonic functions. The average over the expansion coefficients are described by the *angular power spectrum* (APS) as

$$C_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2.$$  

The two-point correlation function can then be derived as

$$C(\theta) \equiv \langle \delta T (\hat{n}) \delta T (\hat{n}') \rangle = \sum_{\ell} \frac{2\ell + 1}{4\pi} C_\ell P_\ell (\cos \theta),$$

where $\cos \theta \equiv \hat{n} \cdot \hat{n}'$ describes the angular separation between the 2 points and $P_\ell$ are
1.1 The $\Lambda$CDM Universe

the Legendre polynomials. The two-point correlation function and the angular power spectrum thus encodes the same information.

Figure 1.1 illustrates the temperature anisotropies (left) and its APS as a function of multipole moment $\ell$ (right), which is related to the length scale through $\ell \approx \pi/\theta$, as observed by Planck (Aghanim et al. 2020). The position and heights of the peaks depend on various processes and contain information on the abundance of baryonic and dark matter (see for details Baumann 2011, 2022). Indeed, the Planck collaboration finds the following precise measurements of the dark matter and baryonic matter abundances,

$$\Omega_{\text{CDM}} h^2 = 0.120 \pm 0.001$$
$$\Omega_b h^2 = 0.0224 \pm 0.0001. \tag{1.4}$$

The dominant feature of the temperature anisotropies comes from small density fluctuations in the plasma, which consists of dark matter and baryons that are tightly coupled to the photons. The fluctuations can gravitationally pull matter within. Meanwhile, radiation pressure builds up and pushes the matter outwards creating oscillations, referred to as baryonic acoustic oscillations. Dark matter interacts only gravitationally and remains within the overdense regions and likewise, after photons decoupled, the baryonic matter remained in the overdense regions.

![Planck observation of the cosmic microwave background (left) and its angular power spectrum (right).](image)

**Figure 1.1:** Planck observation of the cosmic microwave background (left) and its angular power spectrum (right). Image credits: ESA and the Planck collaboration (Aghanim et al. 2020)

Dark matter within overdense regions evolved and formed small halos within overdense regions due to gravitational collapse. The evolution of these small density perturbations can be described at each redshift as

$$\rho(x) = \bar{\rho}[1 + \delta(x)], \tag{1.5}$$
with $\bar{\rho}$ the mean density of the Universe, and $\delta$ the density fluctuations described by a Gaussian random field at location $x$. The density fluctuations can be expanded in Fourier space as follows

$$\delta(x) \equiv \frac{\rho(x) - \bar{\rho}}{\bar{\rho}} = \int \delta(k) \exp(-i k \cdot x) \frac{d^3k}{(2\pi)^3}. \quad (1.6)$$

The two-point correlation function of the fluctuation in the density field is given by

$$\langle \delta(x) \delta(x') \rangle = \int \frac{d^3k}{(2\pi)^3} \frac{d^3k'}{(2\pi)^3} \exp(-i k \cdot x) \exp(-i k' \cdot x') \langle \delta(k) \delta(k') \rangle$$

$$= \int \frac{d^3k}{(2\pi)^3} \exp(-i k \cdot (x - x')) P(k), \quad (1.7)$$

where $P(k) \equiv \langle \delta(k) \delta(k') \rangle / (2\pi)^3 \delta(k + k')$ is the power spectrum which statistically describes the power of the density perturbations from which structure is formed as a function of scale. The matter power spectrum has been accurately measured with the CMB, galaxy large scale structure, weak lensing of galaxy shapes and the Lyman-\(\alpha\) forest, as illustrated in Figure 1.2.

The evolution of density fluctuations can be described analytically at large scales ($\delta \ll 1$), as the density fluctuations are described by Gaussian statistics. At small scales ($\delta \gg 1$) structure is formed, and the the evolution of the density fluctuations can be modeled using numerical simulations or, through analytical models by making assumptions on the collapse of structure. One such model is the spherical collapse model, in which a uniform and spherical perturbation evolves independently in the expanding Universe. Once its density is $18\pi^2 \simeq 178$ times larger than the average density of the Universe, they will gravitationally collapse and form a virialized object. These objects are dark matter halos. Smaller dark matter halos form first and grow and merge to form larger halos. This was statistically described by Press & Schechter in 1974 (Press & Schechter 1974), and is known as the Press-Schechter formalism. The Press-Schechter formalism describes the fraction of dark matter halos of a certain mass within a volume, and it has been further extended and improved (see, e.g., Bond et al. 1991; Bosch 2002; Cooray & Sheth 2002; Schneider et al. 2013). Within dark matter halos, gas falls inside due to their gravitational pull, and when the halo is cool enough the gas collapses to form stars. The first stars were formed when the temperature was around $T = 4$ meV and are called population III stars. Galaxies were formed after, and they evolved as the clusters and superclusters of galaxies that we observe today.

### 1.2 Evidence for dark matter

In the very late Universe, astronomers and physicists started to find missing matter in the 1930s by estimating the amount of matter in galaxies and galaxy clusters. In
1.2 Evidence for dark matter

Figure 1.2: The matter power spectrum at $z = 0$ from CMB observations by Planck, cosmic shear observations by DES YR1, galaxy clustering observations by SDSS and Lyman-$\alpha$ forest observations with eBOSS (Chabanier et al. 2019). The black line corresponds to the best-fit power spectrum in $\Lambda$CDM by Planck 2018 (Aghanim et al. 2020).

In particular, there were two important studies. Firstly, the astronomer Fritz Zwicky studied the velocity dispersion of galaxies in the Coma galaxy cluster (Zwicky 1933, 1937). The velocity dispersion he found was much higher than expected, implying that the cluster could not be a gravitationally bound system unless there would be about 400 times more mass than inferred from the visible galaxies. He concluded that most of the mass in clusters therefore must be invisible, and, indeed, similar discrepancies were found in other galaxy clusters (Holmberg 1937; Smith 1936). The second type of study was in the 1970s by Vera Rubin and Kent Ford (Rubin & Ford 1970). They studied the orbital velocity of stars and gas in galaxies as a function of the distance to the center of the galaxy, known as rotation curves. The orbital velocity is described in Newtonian physics as

$$v(r) = \sqrt{\frac{GM(r)}{r}}, \quad (1.8)$$
where the velocity is expected to decrease with distance as the gravitational pull decreases. Through optical spectroscopic analysis of the Andromeda galaxy, they found however that the rotation curves remained constant out to large radii. This implies that more mass is present in the form of a massive halo with mass $M \propto r$. In the following years, rotation curves were extended to larger radii and to a variety of galaxies. These provided hints of the existence of dark matter extending to scales much larger than the galactic disk (Freeman 1970; Roberts & Rots 1973; Rogstad & Shostak 1972; Rogstad et al. 1973). Figure 1.3 illustrates the rotation curve of galaxy NGC 6503, the disk and gas contributions, and the dark matter halo required to fit the data (Freese 2009). Indeed, the rotation curve is flat far beyond the visible disk and gas. Such studies established the foundations of dark matter (see also de Swart et al. 2017).

![Figure 1.3: Rotation curve of galaxy NGC 6503 which consists of a visible disk and gas component as well as a dark matter halo that is required to fit the data (Freese 2009).](image)

Nowadays, there is evidence for dark matter from Galactic to cosmological scales. One such method is by measuring the mass in galaxies and galaxy clusters through gravitational lensing experiments, as introduced in Section 1.4.3. The amount of deflection indicates the amount of mass, which can be compared with the visible matter, and the presence of dark matter has been observed at distances beyond observational reach with rotation curves. One such evidence for the existence of dark matter was found by Clowe et al. (2006) through lensing observations of two colliding galaxy clusters, the Bullet Cluster. The mass observed through gravitational lensing does not
trace the distribution of the baryons, consisting of hot intracluster gas that is observed by X-ray observations. As illustrated in Figure 1.4, the total mass (blue) observed through gravitational lensing cannot be explained by X-rays (red). As observed from the mass distribution, during the collision the hot intracluster gas interacted with each other, while galaxies and stars separate from the gas and pass through. The inferred total mass follows the distribution of galaxies and stars, implying that the dark matter is collisionless as well and must be non-baryonic.

![Image of two colliding galaxy clusters](image)

**Figure 1.4:** Collision of two colliding galaxy clusters (bullet cluster), showing the reconstructed mass distribution based on X-ray emission (red) and gravitational lensing (blue). Image credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al..

Since the 1970s numerical simulations have been developed to reproduce the large-scale structure in the Universe. The density fluctuations in the early Universe evolve in the expanding Universe and gravitationally collapse to form the structure that we observe today. The hierarchical formation of structure starting from the density fluctuations in the early Universe has been found to fit the observed structure in the Universe well, only in the presence of about 10 times more mass than with baryons only (Blumenthal et al. 1984).

Finally, on cosmological scales, measurements of anisotropies in the cosmic microwave background (CMB) provide evidence for dark matter through the APS, as described in Section 1.1.
1.3 Dark matter candidates

Despite the wide range of observational evidence for dark matter, its nature remains unknown. Solutions can be found in alternative gravity theories or in unseen matter, possibly from an unknown particle. Indeed, one of the most popular explanation is that dark matter consist of a new particle, which needs to satisfy the observations previously discussed and summarised as: 1) the interaction with the electromagnetic radiation must be weak as to remain dark, 2) the particle must have a lifetime longer than the age of the Universe (∼13.8 Gyr), 3) it must have the correct relic abundance. None of the particles in the standard model can satisfy these conditions and it is necessary to search beyond. The dark matter particle’s mass is however only very weakly constrained, ranging from ultra-light (10⁻²¹ eV) to ultra-heavy (10 solar mass), making the search challenging. In this thesis, I focus on particle dark matter with a mass between keV up to PeV. In the following, I discuss the production of candidates relevant for this study (see however Bertone et al. 2005 for an extended review on different candidates).

1.3.1 Thermal dark matter

Dark matter particles that were in thermal and chemical equilibrium with the hot plasma in the early Universe are referred to as thermal dark matter particles. Thermal dark matter particles interacted with standard model particles in the plasma through $\chi \bar{\chi} \leftrightarrow \text{SM SM}$, with $\chi = \bar{\chi}$ if dark matter is its own antiparticle (Majorana particle). The evolution of its number density, $n$, is described by the following Boltzmann equation

$$\frac{d(na^3)}{a^3dt} = \frac{dn}{dt} + 3Hn = \langle \sigma v \rangle (n_{eq}^2 - n^2),$$

where $n_{eq}$ is the number density of dark matter in thermal equilibrium, and $\langle \sigma v \rangle$ the thermally averaged annihilation cross-section of $\chi \bar{\chi}$. At high temperatures, the production and annihilation rate were equally efficient and the dark matter number density was conserved ($n = n_{eq}$). When the temperature dropped, the number density became exponentially suppressed as the interaction rate decreased due to the expansion of the Universe. Indeed, the expansion rate became dominant and dark matter particles were too diluted to interact, resulting in a freeze-out from the plasma with a number density, observable today as the relic abundance of dark matter $\Omega_{DM}$. Figure 1.5 illustrates the evolution of the comoving number density, which is defined as $N = n/s$ with $s$ the entropy density. Increasing the cross-section will increase the interaction rate and therefore, will keep dark matter longer in thermal equilibrium resulting in a smaller relic abundance.

For a dark matter mass with $m_{DM} \sim 100$ GeV, the relic abundance can be roughly
estimated as (Jungman et al. 1996)

\[ \Omega_{DM} h^2 = \frac{m_{DM} n}{\rho_c} \simeq \frac{3 \times 10^{-27} \text{cm}^3\text{s}^{-1}}{\langle \sigma v \rangle}. \] (1.10)

Given the observed relic abundance today of \( \Omega_{DM} h^2 = 0.1200 \) (Aghanim et al. 2020), the cross-section is roughly estimated to be \( \langle \sigma v \rangle \simeq 3 \times 10^{26} \text{cm}^3\text{s}^{-1} \), corresponding to the cross-section of the weak scale interactions. This has motivated searches for Weakly Interacting Massive Particles, \textit{WIMPs}, and this coincidence has been referred to as the WIMP miracle.
1.3.2 Non-thermal dark matter

Non-thermal dark matter particles were never in thermal equilibrium with the hot plasma of the early Universe. This could be for instance due to feeble interaction strengths with the SM particles, and these dark matter particles are referred to as Feebly Interacting Massive Particles, FIMPs. FIMPs can be produced through the decay and annihilation of heavier particles that are in thermal equilibrium. In this case, the relic abundance is produced through the mechanism called freeze-in (the opposite of the freeze-out mechanism). Indeed, the dark matter abundance increases with time due to the decay and annihilation of heavier particles in the plasma. When the temperature dropped sufficiently to the point that the heavy particles freeze-out and their number density becomes suppressed, the dark matter abundance becomes constant. In the following, I elaborate on two well discussed FIMP candidates.

Sterile neutrinos

The neutrinos in the SM were previously considered to be dark matter (Bergström 2000). However, they are too light, \( m_\nu < 0.8 \text{ eV} \) (Aker et al. 2022), to account for dark matter; they would be relativistic at structure formation time and prevent the formation of galaxies that we observe today. Sterile neutrinos are hypothetical particles that can have much larger mass (keV-scale) and, therefore, be a viable dark matter candidate. Moreover, they are a natural extension to the SM as they can provide solutions to the following issues of the SM.

In the SM, particles receive mass through the Higgs mechanism by switching between left and right handedness. However, while all fermions come in a pair of left and right handed chirality, neutrinos have only left-handed chirality, implying that they cannot acquire mass through this mechanism. Neutrino oscillation experiments found however that neutrinos oscillate between their three flavours, and that neutrinos do have a tiny mass (Kajita 1999; Tanabashi 2018). It is thus likely that a right-handed neutrino exists. The Seesaw mechanism predicts that there are light left-handed neutrinos and heavy right-handed neutrinos, and, that they are Majorana particles (Asaka et al. 2005; Kusenko et al. 2010). As a seesaw, the lighter the left-handed the heavier the right-handed neutrino, which provides an explanation of the observed low mass of the SM neutrinos. Left-handed neutrinos can couple to the weak force (hence known as active neutrinos), while right-handed neutrinos only interact gravitationally (hence known as sterile neutrinos).

Moreover, particles that are their own antiparticles can create an imbalance in the matter anti-matter in the Universe. Astrophysical and particle accelerator observations indeed find such imbalance in the matter anti-matter while the Universe is expected to have started from a state with equal numbers and conserved quantities (Riotto & Trodden 1999). Sterile neutrino decay can generate a lepton asym-
1.3 Dark matter candidates

metry, and thereby creating the imbalance in matter and anti-matter, referred to as
leptogenesis (Canetti et al. 2012; Davidson et al. 2008; Drewes & Garbrecht 2013).
In summary, sterile neutrinos can possibly explain the tiny mass of active neutrinos,
the matter anti-matter asymmetry and dark matter.

Sterile neutrinos are produced through oscillations with active neutrinos, in which
frequent collisions in the early Universe drives the production. The probability of
oscillations is described by mixing angle \( \theta \). In the Dodelson-Widrow production
mechanism, the mixing angle as a function of sterile neutrino mass is fixed to the
value that produces the correct dark matter abundance (Dodelson & Widrow 1994).
This scenario is however excluded by X-ray observations and structure formation
limits (Boyarsky et al. 2019a).

In the presence of a lepton asymmetry, the sterile neutrino production can be
enhanced due to the Mikheyev-Smirnov-Wolfenstein (MSW) resonance (Mikheyev &
Smirnov 1985; Wolfenstein 1978). The oscillation probability is modified by an extra
matter potential and the mixing will be amplified. A large lepton asymmetry thus in-
duces a larger dark matter abundance. The mixing angle required for the correct dark
matter abundance can reach smaller values, and evade the current exclusion limits.
This production mechanism is called the Shi & Fuller mechanism (Shi & Fuller 1999b;
Venumadhav et al. 2016). Sterile neutrinos wiIl generally have colder energy distri-
butions than through the Dodelson-Widrow mechanism as the resonance occurs at a
narrow energy range at lower momenta. The maximum lepton asymmetry value is
bounded by the observed abundances of light elements produced during the BBN (Bo-
yarsky et al. 2009; Serpico & Raffelt 2005), corresponding to a lower bound on the
mixing angle. Another production mechanism that produces a colder distribution is for
instance through the decay of heavy particles in the early Universe (Boyarsky et al.
2019b; Drewes et al. 2017).

Axions and Axion-like particles

Axions are light bosons that were originally proposed to solve the strong CP problem,
which concerns the question why CP (Charge + Parity) conservation is observed in
quark interactions while a violation of the CP-symmetry is allowed (Peccei & Quinn
1977; Weinberg 1978). These type of axions are referred to as the QCD axion, and
their non-thermal production mechanism produces cold axions. They can constitute
dark matter with the relic abundance set by the decay constant \( f_a \), which is related
to the mass through \( m_a \propto 1/f_a \). A thermal production is possible, however, as the
allowed mass range of QCD axions is between \( 10^{-12} \text{ eV} < m_a < 10^{-3} \text{ eV} \) (Abbott &
Sikivie 1983) they would contribute as hot dark matter and is excluded by structure
formation. Axion-like particles are axions that do not solve the strong CP problem
and their mass is unconstrained as it is not related to \( f_a \) (see Marsh 2016 for a review
on axions).
1.4 Small scale issues in ΛCDM

There are various challenges to the ΛCDM model that I described in section 1.1 (see Perivolaropoulos & Skara 2021 for a review). One of the challenges is observed at small scales. The ΛCDM model is able to accurately reproduce the large scale structure in the Universe (Aghanim et al. 2020; Alam et al. 2021), however, there are significant discrepancies between the model predictions and observations on scales smaller than \( \sim 1 \) Mpc (which corresponds to mass scales \(< 10^{11} \text{ M}_\odot \)). This section describes in detail the current challenges that the ΛCDM faces on the small scales.

**Missing satellites problem**

A historical problem of ΛCDM is the missing satellite problem, that states that dark matter-only ΛCDM cosmological simulations overpredict the abundance of satellite galaxies around the Milky Way (Klypin et al. 1999; Moore et al. 1999a). However, the Dark Energy Survey and Pan-STARRS1 have only reported the detection of 270 Milky-Way satellite galaxies (Drlica-Wagner et al. 2020), an order of magnitude less satellites, hence the *missing satellite problem*.

**Too-big-to-fail problem**

Other challenges of ΛCDM numerical simulations are related to the internal structure of dark matter halos. One such problem is the *too-big-to-fail problem*, which states that the most massive subhalos around the Milky Way are too big to fail galaxy formation within and are too dense to host the most luminous observed Milky Way satellites (Boylan-Kolchin et al. 2011, 2012). Similar results have been found in Andromeda (Tollerud et al. 2014) and in galaxies from the Local Group Field (Garrison-Kimmel et al. 2014; Papastergis et al. 2015).

**Core/cusp and diversity problem**

When dark matter collapses, it forms halos with an inner density that scales approximately as \( \rho^{-1} \). This is predicted by N-body simulations (Ferrero et al. 2012; Navarro et al. 1996, 1997; Moore et al. 1999b) and referred to as *cuspy density profiles*. However, the orbital velocity of stars and gas in satellite galaxies are better fitted by an underlying dark matter distribution with a constant density at the core (Agnello & Evans 2012; Amorisco & Evans 2011; Battaglia et al. 2008; Davis et al. 1985; Flores & Primack 1994; Agnello & Evans 2012; Moore 1994; Oh et al. 2015; Walker & Peñarrubia 2011). This type of flat density profile is usually referred to as *cored density profiles*.

The core-cusp problem is nowadays also referred to as the ‘diversity problem’.
1.4 Small scale issues in $\Lambda$CDM

This raises from the rotational curves of dwarf galaxies embedded in same-mass dark matter halos, that depict a large variety in shape and central densities (see, e.g., Oman et al. 2015; Read et al. 2016b; Relatores et al. 2019; Ren et al. 2019; Santos-Santos et al. 2020; Tollet et al. 2016). This is in direct contradiction to the rotational curves from cold dark matter halos, that for these low mass galaxies are expected to follow the same profile, and therefore have the same shape.

**Plane-of-satellites problem**

Another interesting challenge faced by the $\Lambda$CDM relates the spatial distributions of Milky Way satellites. Milky-Way satellites lie in a thin plane (Kroupa et al. 2005), while it has been observed that cosmological simulations indicate that subhalos should be distributed isotropically. Similar correlations in the satellites’ positions have been found in the Andromeda galaxy and the Local Group (Conn et al. 2013). Moreover, the orbits of those Milky-Way satellites appear to be correlated with some satellites of the Andromeda galaxy (Ibata et al. 2014; Pawlowski et al. 2014). Current solutions to this issue are still under debate (see Pawlowski 2018 for details).

1.4.1 Baryonic solutions

After the first stars formed, the intergalactic medium was heated to $\sim 10^4 \text{ K}$ due to cosmic reionization. This ionization process prevents the gas from collapsing within dark matter halos due to the increased gas pressure, consequently preventing stars to form (Gnedin et al. 2004; Okamoto et al. 2008). This might alleviate the missing satellite problem as some dark matter halos might remain dark and be unable to re-accrete any gas (see, e.g., Boylan-Kolchin et al. 2014; Bullock et al. 2000; Shapiro et al. 2004; Weisz & Boylan-Kolchin 2017).

Baryonic matter could also be blown away from the dark matter halo through for instance supernova feedback. During strong periods of star formation, supernova-driven winds are able to expel baryonic matter out of the galaxies’ potential wells (Navarro et al. 1996). This process prevents gas from cooling and forming stars. Moreover, dark matter is moved outwards too due to energy transfer from baryons, this consequently produces a cored density profile (Chan et al. 2015; Di Cintio et al. 2014; Garrison-Kimmel et al. 2013; Mashchenko et al. 2008; Pontzen & Governato 2012; Read & Gilmore 2005; Tollet et al. 2016). This might help solving the cusp/core problem, as well as the too-big-to-fail problem (Madau et al. 2014; Zolotov et al. 2012).

Finally, when a satellite galaxy is in close orbit with their host halo, it can lose mass due to tidal stripping, halo shocking and disk shocking. This potentially leads to small subhalos to be completely disrupted, possibly helping to solve the missing satellite problem (Arraki et al. 2014; Brooks & Zolotov 2014; D’Onghia et al. 2010).

Hydrodynamical simulations that include baryonic effects have shown to repro-
duce well the observed galaxy properties (Springel et al. 2018). The uncertainties in baryonic physics are however large, and the small scale problems of the ΛCDM are only alleviated under specific assumptions of the baryonic processes (Nelson et al. 2019; Rosdahl et al. 2017; Schaye et al. 2015). Moreover, the numerical resolution of these simulations is limited, and generally not sufficient to resolve the scales in which stars and galaxies form. To overcome this, zoom-in simulations of individual galaxies and galaxy groups have been performed. Zoom-in simulations will however be statistically biased, since it is not possible to make general and statistical statements on galaxy formation. Therefore, in order to resolve the small scale problems of the ΛCDM with baryonic physics, improved numerical resolutions are crucial in combination with careful comparison with observations, as well as accurate (semi-)analytical models that describe the formation and evolution of dark matter halos with baryonic processes.

1.4.2 Non-baryonic solutions

Solutions can also be found in deviations from the standard ΛCDM model. Dark matter candidates that suppress structure formation on small scales while behaving as CDM on large scales would be for instance viable candidates. Warm dark matter are such particles that are almost relativistic during structure formation times, in contrary to cold dark matter that have negligible thermal velocities during structure formation time. This allows them to free-stream out of small density perturbation below a free-streaming scale, while forming structure similar to the case of CDM above the free-streaming scale. Due to the suppression of structure, the formation of halos will be delayed. Halos are therefore formed when the Universe was less dense, producing less dense halos, and warm dark matter can possibly solve both the too-big-to-fail problem and the missing satellite problem. Moreover, due to their large thermal velocities dark matter halos are flattened and produce constant cores, possibly solving the cusp/core problem (Destri et al. 2013; Maccio et al. 2012; Villaescusa-Navarro & Dalal 2011). However, some work find that warm dark matter does produce cored profiles (Kuzio de Naray et al. 2010) and it is not clear whether dark matter can solve this issue (see Del Popolo & Le Delliou 2021 for a review).

The suppression of structure due to warm particles leaves an imprint on the matter power spectrum through a cut-off at small scales. It can be described by the transfer function $T(k)$:

$$P_{WMD}(k) \equiv T^2(k)P_{CDM}(k).$$  \hspace{1cm} (1.11)

Based on cosmological simulations, Viel et al. (2012) find the following fitting formula
for the transfer function

\[ T^2(k) = (1 + (\alpha k)^{2\nu})^{-5/\nu}, \]

\[ \alpha(m_{\text{WDM}}) = 0.049 \left( \frac{1 \text{keV}}{m_{\text{WDM}}} \right)^{1.11} \left( \frac{\Omega_{\text{WDM}}}{0.25} \right)^{0.11} \left( \frac{h}{0.7} \right)^{1.22}, \] (1.12)

with \( \nu = 1.12 \). Figure 1.6 illustrates the matter power spectrum for cold and warm dark matter. The warmest particles show the largest suppression of small scale density perturbations. A lower bound on the dark matter mass can be obtained for which too much structure is erased, and it is the topic of Chapter 4.

As another solution, dark matter could be collisional and interact with itself, known as self-interacting dark matter (SIDM), and has been proposed to solve the cusp/core and missing satellite problems (Spergel & Steinhardt 2000). SIDM has a large scattering cross-section which can be either temperature dependent or constant. The mass is only weakly constrained and SIDM could be even warm (Colin et al. 2000). Collisional particles will reduce the central density as self-interactions will transport heat to cooler regions which are at the outer regions of the dark matter halo and produce a cored profile, solving both the the cusp/core and too-big-to-fail problems (Loeb & Weiner 2011; Rocha et al. 2013; Vogelsberger & Zavala 2013). Meanwhile, if the cross-section is proportional to the dark matter density, large SIDM halos will be consistent with CDM as the collision rate is negligible (Tulin & Yu 2018).
1.4.3 Small scale observations

Small scale observations can thus be used to distinguish dark matter models, and the thermal mass has indeed been constrained through various observational techniques. One such technique is through gravitational lensing, in which photons are detected that are emitted at distant astrophysical sources and deflected by a massive object, such as a galaxy cluster, as predicted by Einstein’s theory of General Relativity. The amount of deflection depends on the gravitational potential given by the dark matter within the main lensing object, the subhalos around the object, and the dark matter halos along the line of sight. By studying gravitationally lensed quasars, lower limits are set at $m > 5.58$ keV (Gilman et al. 2019; Hsueh et al. 2020; Nadler et al. 2021a; Vegetti et al. 2018). The advantage of this type of analysis is that it does not rely on baryonic physics and solely on the gravitational potential of dark matter. Systematic uncertainties for gravitational lensing are the stellar structures in the lensed galaxy, as well as the structure of the quasars which is assumed to be point-like, and variations in the background source (Hsueh et al. 2020).

Another technique is the study of the continuum light from distant quasars that is expected to show absorption features due to gas clouds along the line of sight at different redshifts, called the Lyman-α forest. As dark matter is expected to supply the gravitational potential well to hold the gas together, the Lyman-α forest will map out dark matter halos along the line of sight. Studies by Enzi et al. (2021); Iršič et al. (2017); Murgia et al. (2018) find lower limit on the dark matter mass of $> 5.3$ keV. Systematic uncertainties are the mean flux of the quasars and the assumptions on the intergalactic medium, such as the effective optical depth, which affect the results (Garzilli et al. 2017).

Lastly, the abundance of satellite galaxies in the Milky-Way can be counted. Lower limit on the thermal warm dark matter mass have been found at $> 9.0$ keV (Cherry & Horiuchi 2017; Dekker et al. 2021a; Nadler et al. 2021b; Newton et al. 2021). Systematic uncertainties lie in the connection between galaxies and dark matter halos, the detectability of Milky-Way satellite galaxies and the size of the Milky-Way halo mass.

1.5 Dark Matter detection

The only evidence for dark matter is based on gravitational observations, while a direct observation would confirm its nature. There are various methods to detect dark matter which all come with their strengths and weaknesses, illustrating the importance of combining the information from various searches. Figure 1.7 illustrates the dark matter interactions with SM particles and their following detection techniques which will be discussed: (a) indirect detection aims to detect standard model particles that are produced when dark matter decays or annihilates, (b) direct detection aims
to detect dark matter scattering with SM particles in Earth based detectors, (c,d) collider experiments search for dark matter that are produced when SM particles annihilate within particle colliders and this production can occur through a mediator (d) (Buchmueller et al. 2017).

Figure 1.7: Dark matter interactions and their corresponding experimental detection techniques: indirect detection (a), direct detection (b) and collider searches (c,d) (Buchmueller et al. 2017).

1.5.1 Direct Detection

One natural way to detect dark matter particles is by direct detection, in which a WIMP dark matter particle scatters off an atomic nucleus. The momentum transfer will give rise to a nuclear recoil event, which can be observed with experiments. The interaction rate is low. Therefore, large detectors are built deep underground to shield against background events, which are mainly coming from cosmic rays. The expected rate of DM-nucleon scattering in a detector is given by (Schumann 2019):

\[
\frac{dR}{dE_r} = \frac{\rho_{DM} M}{m_N m_\chi} \int_{v_{\text{esc}}}^{v_{\text{min}}} v f(v) \frac{d\sigma}{dE_r} dv, \tag{1.13}
\]

where \(E_r\) is the nuclear recoil energy, \(m_N\), \(M\) and \(m_{DM}\) are the mass of the nuclei, detector and WIMP, \(\rho_{DM}\) is the local dark matter density, \(\sigma\) is the interaction cross-section. Moreover, \(f(v)\) describes the distribution of WIMP velocities in the Milky Way, which is typically modelled with a Maxwellian distribution in an isotropic isothermal sphere, and is bounded between the minimum velocity (\(v_{\text{min}}\)) necessary to produce a recoil energy \(E_r\), and the escape velocity (\(v_{\text{esc}}\)) of the potential well of the Milky Way. The aim of these experiments is to determine the mass and the scattering cross-section of the WIMP. Based on the non-detection of any WIMP signal, various experiments exclude regions of initial interest. Figure 1.8 summarizes the current constraints at 90% on the spin-independent cross-section, in which the scattering does not depend on the spin of the target nucleus (Billard et al. 2022). In the
case that WIMPs couple to the spin of the nuclei, the scattering cross-section could be lower due to opposing spin signs, and this will result in weaker limits. The current strongest limits come from XENON1T collaboration, which is an underground liquid xenon detector (Aprile et al. 2018, 2021). The yellow dashed line is the neutrino floor, which is the limit where neutrinos from the sun, atmosphere or the diffuse supernova background, will dominate the nuclear recoil searches, although efforts are in place to go beyond this limit (Billard et al. 2014, 2022).

![Figure 1.8: Current status of direct dark matter detection for spin-independent scattering cross-section (Billard et al. 2022).](image)

### 1.5.2 Collider searches

Complementary searches are performed by experiments that produce WIMPs at high energy particle colliders. The current leading sensitivity comes from The Large Hadron Collider at CERN (Aad et al. 2013; Khachatryan et al. 2015). Through the annihilation of two high-energy protons, dark matter particles are inferred. The final states after collision are reconstructed, where dark matter particles will escape the detector. This will create an imbalance in the transverse momentum, which is a conserved quantity, and yield a dark matter detection. Likewise, mediators can be
probed in these searches, which are particles that interact both with SM particles and dark matter. It is possible that these mediators are observable in interactions with SM particles only. However, the observation of a mediator would indicate the mass range of dark matter particles, which will accommodate future searches. In order to compare results with direct and indirect detection, it is necessary to adopt the same underlying theoretical model, and details on the decay and production in particle colliders are required (Boveia et al. 2020).

### 1.5.3 Indirect searches

Dark matter particles can decay or annihilate with their own (anti-)particle, and their final products can be detected as cosmic rays, photons or neutrinos from astrophysical regions on the sky. Due to large length scales and high dark matter density within astrophysical environments, indirect searches offer a way to explore up to very high energies, long decay lengths and weak scattering cross-sections. The highest dark matter flux observable at Earth is coming from the Galactic center, as the Milky Way is embedded in a dark matter halo with increasing flux towards the inner region. The main focus of my thesis is therefore to identify dark matter signals using photons and neutrinos from the Galactic center.

The flux from a secondary particle $i$ (photon, neutrino or cosmic ray) produced when dark matter particles with mass $m_{\text{DM}}$ decay ($\alpha = 1$) or annihilate ($\alpha = 2$) is described as follows

$$
\frac{d\Phi_i}{dE} = \frac{dN_i}{dE} \frac{\Gamma}{4\pi m_{\text{DM}}^2} \int d\ell \rho^\alpha, \tag{1.14}
$$

where $\frac{dN_i}{dE}$ is the energy spectrum of the secondary particles, which depends on the decay or annihilation channel. Moreover, $\Gamma$ is the interaction rate of dark matter particles. For dark matter decay it is given by $\Gamma = 1/\tau$, where $\tau$ is the dark matter lifetime, and for dark matter annihilation it is given by $\Gamma = \langle \sigma v \rangle / 2$, which gives the average of the velocity distribution of the annihilating dark matter cross-section multiplied by the relative velocity of annihilating particles. Finally, the last term in Eq. 1.14 is the integral over the dark matter density $\rho$ along the line of sight $\ell$, known as the $D$-factor for decay and $J$-factor for annihilation.

The distribution of the dark matter density can be extrapolated from numerical simulations as discussed in Section 1.4.3. One of the most commonly used distribution is the Navarro-Frenk-White (NFW) profile, which has a steep slope in the inner radii and therefore referred as a cuspéd profile, given as follows (Navarro et al. 1996; Navarro et al. 1997)

$$
\rho(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}, \tag{1.15}
$$
with \( r_s \) the scale radius and \( \rho_s \) the characteristic density at the scale radius. The normalisation and shape of the distribution is however uncertain and will consequently affect dark matter constraints. Indeed, more recent numerical simulations find a better fit with the Einasto profile (Einasto 1965; Navarro et al. 2010) which is likewise a cusped density profile but with the inner density slope left as a free parameter

\[
\rho(r) = \rho_s \exp \left( -\frac{2}{\alpha} \left( \frac{r}{r_s} \right)^\alpha - 1 \right)
\]  

(1.16)

where \( \alpha \) varies for different simulations between \( \sim [0.1, 0.25] \). Small scale observations of galaxies find however a better fit with cored density profiles, and one such commonly used profile is the Burkert profile (Burkert 1995)

\[
\rho(r) = \frac{\rho_s r_s^3}{(r_s + r)(r_s^2 + r^2)}.
\]

(1.17)

Figure 1.9 illustrates the shape of various density profiles as a function of the radius.

Figure 1.9: The NFW, Einasto and Burkert dark matter density profiles as a function of the radius from the center of the halo. The following constants are adopted: \( \rho_s = 0.61 \text{ GeV/cm}^3 \) and \( r_s = 15 \text{ kpc} \) (NFW), \( \rho_s = 0.15 \text{ GeV/cm}^3 \) and \( r_s = 15 \text{ kpc} \) (Einasto), \( \rho_s = 1.72 \text{ GeV/cm}^3 \) and \( r_s = 9.26 \text{ kpc} \) (Burkert).
### 1.5 Dark Matter detection

#### Dark matter searches with X-rays

Warm dark matter candidates such as sterile neutrinos and axion-like particles with keV-scale mass can directly decay into photons and produce a monochromatic X-ray line, detectable by X-ray telescopes. Following a stacked X-ray spectrum analysis of 73 galaxy clusters, a potential signal line was indeed detected at \( \sim 3.5 \) keV (Bulbul et al. 2014a) which could be explained by a sterile neutrino with mass \( m_{\nu_s} \sim 7 \) keV. Various other studies followed-up by using various X-ray instruments and dark matter dominated objects, which both confirmed (Boyarsky et al. 2014b, 2015; Cappelluti et al. 2018; Franse et al. 2016; Iakubovskyi et al. 2015; Neronov et al. 2016) and rejected the signal (Anderson et al. 2015; Bhargava et al. 2020; Dessert et al. 2020a; Foster et al. 2021; Malyshev et al. 2014a; Riemer-Sørensen et al. 2015; Tamura et al. 2015; Urban et al. 2015). The discrepancy is actively debated, and could be originating from analytical modeling; the choice of energy windows or correctly modeling of backgrounds (Abazajian 2020; Boyarsky et al. 2020; Dessert et al. 2020b). As another possibility, there could be a contamination from potassium and chlorine plasma lines (Boyarsky et al. 2014a; Bulbul et al. 2014b; Gu et al. 2015; Jeltema & Profumo 2015, 2014; Shah et al. 2016). In order to distinguish the signal from astrophysical or instrumental lines, improved X-ray telescope are necessary with high energy resolution (Slatyer 2021). Relevant background signals for such searches are spectral lines from atomic processes and the diffuse cosmic X-ray background from unresolved astrophysical sources (Lumb et al. 2002). There are various upcoming X-ray telescopes such as Micro-X, XRISM, Athena, Lynx and eROSITA, which latter one will be the focus of Chapter 3.

#### Dark matter searches with neutrinos

Heavy dark matter candidates with mass-scales in the GeV to PeV energy can be probed with high energy neutrino data. As neutrinos are neutral and interact only very weakly with other particles, they can escape dense environments and travel long distances unattenuated, whereas photons and cosmic-rays might be absorbed and deflected by magnetic fields. The consequence of the weak interactions of neutrinos is however that they are difficult to detect, leading to very large instruments. AMANDA and ANTARES were the first detectors to search for high-energy astrophysical neutrinos by using respectively the ice of the south pole and water from the Mediterranean Sea as detectors. The first evidence of high-energy astrophysical neutrinos was found by the successor of AMANDA in 2013 by the cubic kilometer ice detector IceCube (Aartsen et al. 2013, 2014). Although the effective area of IceCube is huge, its sensitivity is still too limited to significantly detect sources. Indeed, only two neutrino events are possibly associated to active galaxies TXS 0506+056 and NGC 1068 (Aartsen et al. 2020, 2018a,b). The proposed next generation IceCube-
Gen2 aims to enhance IceCube’s neutrino event rate with an order of magnitude by 2033 (Aartsen et al. 2021). KM3NeT is the successor of ANTARES, a network of neutrino detectors that are currently under construction. KM3NeT-ARCA is a cubic kilometer water detector, and is expected to be completed by the end of 2022 (Biagi 2022) and will be observing high-energy astrophysical neutrinos (TeV-PeV) with a high angular precision of $\sim 0.1^\circ$ (Adrian-Martínez et al. 2016a; Fermani 2020).

When a neutrino traverses earth, it can interact with a nucleon, producing muon, tau or electrons. These charged particles will produce Cherenkov radiation if they travel faster than the speed of light within the medium. This is detectable with photomultiplier tubes as a cone (track topology induced by muons) or sphere (shower topology induced by all flavours). Track events have the advantage of having long length scales of $\sim 1$ km, improving the angular resolution and increasing the detector’s volume as the interaction can occur outside of the detector, while shower events have a better energy resolution and lower background contamination. Below $\sim 100$ TeV, the observed neutrino flux is dominated by atmospheric muons and atmospheric neutrinos that are produced when cosmic rays enter the atmosphere. These backgrounds can be reduced by using the earth as a shield; selecting only up-going muon track events or shower events that started within the detector.

Above $\sim 100$ TeV, the largest background comes from the diffuse astrophysical background. The spatial distribution of the observed neutrino events by IceCube is isotropic, suggesting that the dominant contribution to the flux is of extra-galactic origin. Resolving these sources would decrease the background, however, the origin of the individual astrophysical events are primarily unknown. Astrophysical neutrinos can be produced within or in the environment of cosmic ray acceleration sites through interactions with the gas ($p + p$) or radiation ($p + \gamma$), in which neutrinos are produced through the decay of charged pions. Gamma-rays are produced alongside through the decay of neutral pions and can thus hint towards possible neutrino sources. A temporal and spatial connection with neutrinos would result in evidence of the neutrino origin, as well as evidence for hadronic interactions at cosmic-ray accelerators. The non-detection of multi-messenger information lead to upper limits on the contribution to the total neutrino flux of various source classes (Kurahashi et al. 2022). There are various possible explanations for the non-detection of the sources; neutrinos are produced in sources where gamma-rays are attenuated due to high opacity, sources are at far distances which are difficult to detect with gamma-rays, a large fraction of gamma-rays are not produced through hadronic interactions, and, neutrinos could come from decaying or annihilating dark matter particles through channels where mainly neutrinos are produced.

Indeed, dark matter can decay or annihilate directly into two neutrinos, which would result in a monochromatic neutrino line. Figure 1.10 shows the current (solid) and future (dotted, assuming 5 years observation) upper limits on the dark matter annihilation cross-section from various instruments by studying the diffuse emission from
1.5 Dark Matter detection

the Galactic center adopting a likelihood analysis (Argüelles et al. 2021). ANTARES
has the strongest constraints for dark matter mass of $1 - 100$ TeV, due to its location
at the Northern hemisphere which enables observation of the Galactic center with
up-going track events. Above 100 TeV, IceCube has the strongest constraints due
to its large volume. Future instruments KM3NeT, P-ONE and IceCube-Gen2 will
significantly improve the detectability of dark matter. The solid gray line illustrates
the unitarity bound, which gives the maximum cross-section for thermally produced
dark matter particles (Griest & Kamionkowski 1990a). The gray horizontal dotted
line is the cross-section expected to obtain the thermal relic abundance.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure10.png}
\caption{Upper limits at 90\% on the cross-section of dark matter annihilating to neu-
trinos ($\text{DM} \rightarrow \nu \nu$) from various current (solid) and future (dashed) instruments (Argüelles
et al. 2021).}
\end{figure}

\textbf{Angular Power Spectrum analysis}

One way to disentangle an astrophysical from dark matter origin is by studying the
angular distribution of individual neutrino events. Whereas dark matter events are
expected to show a correlation with the Galactic dark matter halo, extra-galactic
astrophysical sources will show an isotropic distribution. An astrophysical galactic
contribution is expected to contribute as well, both from discrete sources as from
the diffuse emission from cosmic-ray interactions, although this contribution is small
($\lesssim 10\%$) (Aartsen et al. 2017a; Ahlers et al. 2016). This galactic signal would be
correlated with the galactic bulge and disc, while the dark matter halo has a more
extended morphology. Using only angular information yields weaker constraints with respect to a likelihood analysis, however, the limits are stable against uncertainties of the density profile and the decay or annihilation channel, offering model-independent and robust constraints. Such analysis can be done through the APS, which assesses angular characteristics on sky maps, as discussed in 1.1 in the context of CMB. Here, the temperature anisotropy $\delta T$ in equation 1.1 is replaced by the number of neutrino events at each point on the sky $\delta N$.

Analyzing the APS of the neutrino sky can reveal the dominant extra-galactic astrophysical sources too (Dekker & Ando 2019). Bright and rare astrophysical source classes will produce anisotropic features on the sky due to clustering of events, and is excluded by the observed isotropic neutrino sky. With the current 10-years of IceCube data we can for instance exclude BL Lacs as dominant contributors, which are a type of active galactic nuclei. Figure 1.11 shows the local number density as a function of the neutrino luminosity of various astrophysical sources. The gray region represents the 95% future exclusion limit based on the APS analysis adopting 10 years of IceCube-Gen2 observations of an isotropic neutrino sky. The blue and red lines represent the parameter space that sources need to have in order to explain the observed diffuse flux for 100% and 10% respectively. We find that flat-spectrum radio quasars (FSRQs) are expected to show a significant clustering of events, and will be observable in the future, offering the opportunity to test such sources. Galaxy clusters (GCs) and BL Lacs are too bright to explain the diffuse flux and are expected to be significantly constraint. Finally, low-luminosity active galactic nuclei (LL AGNs), Fanaroff-Riley galaxies of type II (FRII) and starburst galaxies (SBGs) are consistent with the isotropic neutrino emission and are expected to be detected with IceCube-Gen2, while Fanaroff-Riley galaxies of type I (FRI) will be too weak to be observed. KM3NeT-ARCA has a comparable sensitivity to IceCube-Gen2 and these future instruments are thus expected to resolve many dominant astrophysical sources. In Chapter 2, I discuss applying the APS analysis to probe dark matter particles.
Figure 1.11: Exclusion regions at 95% with 10 years of IceCube-Gen2 for various astrophysical sources adopting an APS analysis (gray) (Dekker & Ando 2019).
Dark matter detection with neutrino telescopes

Abstract

The origin of high-energy neutrinos that have been observed by IceCube in the last decade remains unknown and part of them could be coming from decaying or annihilating dark matter. Indeed, experimental developments in neutrino telescopes are improving their ability to constrain dark matter parameters. Neutrino signals from dark matter are expected to have some correlation with the extended galactic dark matter halo, allowing to distinguish between dark matter and astrophysical origin.

In this chapter, I discuss an angular power spectrum analysis of simulated neutrino sky maps to probe dark matter signals with current IceCube and future IceCube-Gen2 and KM3NeT neutrino telescopes. Interestingly, IceCube observed a tension among different data-sets in the high-energy neutrino flux which can be explained by a dark matter component in addition to the standard astrophysical power-law component. In the first part of this chapter, I discuss the two-component hypothesis and provide current (10-years IceCube) constraints and expected sensitivity to dark matter parameters with future data (10-years IceCube-Gen2 and KM3NeT). KM3NeT is found to be more sensitive than IceCube-Gen2 to look for a dark matter signal at low energies towards the galactic center. Therefore, we perform a similar analysis with KM3NeT and provide model-independent bounds as well as model-dependent bounds considering minimal extensions to the SM for annihilating dark matter channels.

This work is based on Dekker et al. (2020) and Basegmez Du Pree et al. (2021)
2 Dark matter signals from the galactic halo with neutrino telescopes

2.1 Introduction

If neutrinos are products of cosmic-ray accelerators, the neutrino spectrum is expected to follow a power-law, derived from the first-order Fermi shock acceleration as being proportional to $E^{-\gamma}$, with $2.0 \lesssim \gamma \lesssim 2.2$ (Waxman & Bahcall 1999). Furthermore, combining with gamma-ray data from Fermi-LAT observations, upper limits are put on the spectral index for the hadronic scenario of $\gamma \lesssim 2.1 - 2.2$ (Murase et al. 2013; Tamborra et al. 2014; Ando et al. 2015; Bechtol et al. 2017). This is in a good agreement with the recent best-fit $\gamma_{\text{TG}} = 2.28^{+0.08}_{-0.09}$ of through-going (TG) muon neutrinos with 10 years of IceCube observation (Stettner 2019). On the other hand, the 7.5-year High-Energy Starting Events (HESE) data-set prefers a steeper spectrum with a best-fit index of $\gamma_{\text{HESE}} = 2.89^{+0.3}_{-0.19}$ (Schneider 2019). These two measurements are slightly in tension, suggesting that the observed neutrino spectrum does not fit very well with the assumption of a single power-law component. Remarkably, such a tension is strengthened by combining IceCube and ANTARES data (Chianese et al. 2017a). It is worth noticing that the TG data-set observes only the northern sky above 200 TeV, while the HESE data contains astrophysical neutrinos from the full sky, including the galactic center, with an energy larger than about 60 TeV. This motivates a two-component scenario, one extragalactic isotropic component with $\gamma \simeq 2.0$, and a second, possibly galactic, component with a steeper spectrum (Chen et al. 2015; Aartsen et al. 2015a; Chianese et al. 2016; Palladino et al. 2016; Palladino & Vissani 2016; Palladino & Winter 2018; Vincent et al. 2016; Anchordoqui et al. 2017; Sui & Bhupal Dev 2018). The latter is required to account for an excess in neutrino events at around 100 TeV (Chianese et al. 2016, 2017b,a,c). Different interpretations of such an excess have been proposed so far: hidden astrophysical sources where gamma-rays are highly absorbed due to the source’s opacity (Kimura et al. 2015; Murase et al. 2016; Tamborra & Ando 2016; Senno et al. 2016; Denton & Tamborra 2018a,c), invisible decay of active neutrinos (Denton & Tamborra 2018b), or decaying dark matter (DM) particles (Chianese et al. 2016, 2017b,c, 2018, 2019).

A detectable flux of high-energy neutrinos might indeed originate from the decay of heavy DM particles (Chianese et al. 2016, 2017b; Chianese & Merle 2017; Chianese et al. 2017c, 2018, 2019; Anisimov & Di Bari 2009; Feldstein et al. 2013; Esmaili & Serpico 2013; Esmaili et al. 2014; Bai et al. 2016; Ema et al. 2014a,b; Bhattacharya et al. 2014, 2017, 2019; Higaki et al. 2014b; Rott et al. 2015; Fong et al. 2015; Dudas et al. 2015; Kopp et al. 2015; Murase et al. 2015; El Aisati et al. 2015; Anchordoqui et al. 2015; Boucenna et al. 2015; Ko & Tang 2015; Dev et al. 2016a,b; Re Fiorentin et al. 2016; Di Bari et al. 2016; Borah et al. 2017; Hiroshima et al. 2018b; Sui & Bhupal Dev 2018; Pandey et al. 2019b,a). On the other hand, a neutrino signal from annihilating DM particles is in general suppressed by the unitarity limit, except in case of very cold DM substructures (Feldstein et al. 2013; Zavala 2014; El Aisati et al. 2017; Bhattacharya et al. 2019). Current neutrino and gamma-ray data place constraints...
on both decaying and annihilating DM scenarios (Albert et al. 2017; Abeysekara et al. 2018; Aartsen et al. 2018c; Argüelles & Dujmovic 2019; Iovine et al. 2019). Multi-messenger analyses based on the observations of neutrinos and gamma-rays are indeed of paramount importance when examining potential heavy DM signals (Cohen et al. 2017; Neronov et al. 2018; Blanco & Hooper 2019; Ishiwata et al. 2020). In particular, the Fermi-LAT measurements strongly constrain DM decays into hadronic final states due to large production of gamma-rays as primary and secondary particles. On the other hand, present data do not exclude the presence of a second component in the neutrino flux coming from leptophilic decaying DM particles, especially when the astrophysical power-law component is assumed to follow the prior deduced by through-going muon neutrinos (Chianese et al. 2019).

While the expected neutrino energy spectrum from astrophysical sources and DM particles might be similar, they exhibit very different angular distributions for the arrival directions of neutrino events. In particular, astrophysical sources are expected to be uniformly distributed in the full sky, while DM neutrino signal has some level of correlation with the galactic center where a high density of DM particles is typically expected. Such a difference in the angular distribution is therefore a key feature that would allow one to firmly discriminate between astrophysical and DM neutrino fluxes. Different analyses have pointed out that a galactic contribution consistent with gamma-rays can only account for less than 10% of the observed neutrino flux (Ahlers et al. 2016; Denton et al. 2017; Aartsen et al. 2017a) (see also Chianese et al. (2016)). These studies assume the galactic contribution to correlate with the galactic bulge and disc, as expected for astrophysical galactic sources. On the other hand, angular studies based on a more extended template for the galactic contribution have instead shown a preference for a galactic component in the neutrino flux (Esmaili et al. 2014; Chianese et al. 2016; Neronov & Semikoz 2016b,a). In this context, a DM signal would indeed contribute to the neutrino data as a quite extended galactic diffuse emission identified with the DM halo, as well as an extragalactic isotropic emission. These two galactic and extragalactic DM contributions can be of the same order of magnitude depending on the DM model considered.

In the first part of this chapter, we investigate the two-component hypothesis (astrophysical power-law plus a DM signal) by analyzing only the angular distribution of the simulated neutrino sky maps by using the angular power spectrum. We test our two-component hypothesis with Monte Carlo method for a wide range of values for the lifetime and cross-section of the Dark Matter models. We assume the astrophysical component to be fixed by the 10-year through-going muon neutrinos data (Stettner 2019), while we consider different models for the DM halo profile and boost factor, which provide different angular distributions for the DM component. Under the assumption of an isotropic neutrino flux, we place a constraint on the level of anisotropy induced by a DM component, which is then translated to a bound for DM lifetime and cross-section in case of decaying and annihilating DM particles, re-
spectives. The two-component model is therefore tested for various DM parameters with 6-year of HESE observations, as well as for future neutrino data with IceCube-Gen2 (Ackermann 2017) and KM3NeT (Adrian-Martinez et al. 2016b) exposures. While the former will collect many more neutrino events thanks to the larger volume, the latter is expected to be more sensitive to the galactic center and, consequently, to a potential DM component. Our current and future constraints are weaker than the ones reported in other analyses, but they are more robust since they rely only on the angular distribution of neutrinos. However, we show that, after 10 years of observation, IceCube-Gen2 and KM3NeT will firmly probe the current best-fit for the DM contribution of the two-component flux reported in Chianese et al. (2019), thanks to the expected clustering of events towards the galactic center.

In the second part of this chapter, we investigate the potential sensitivity of KM3NeT to derive model-independent bounds for various dark matter annihilation channels into SM particles at lower energies (from 200 GeV to $10^5$ GeV). These sensitivities are the basis to elaborate on the particle physics implications for the dark matter searches and complementary studies. Therefore, we consider different models where neutrino telescopes would likely be the most constraining in the future, and consider a subset of the minimal models investigated in El Aisati et al. (2017). Our model building procedure is motivated by the requirements of unitarity, gauge invariance and anomaly free, see e.g. the discussion in Kahlhoefer et al. (2016); Ellis et al. (2017), and builds on top of the simplest realisation of single mediator models to end up with the known gauged $L_{\mu-\tau}$ model (He et al. 1991a,b; Foot et al. 1994; Baek et al. 2001; Ma et al. 2002; Heeck & Rodejohann 2011; Altmannshofer et al. 2014b). In this study, we consider Dirac dark matter, which has the potential of the most promising signatures for neutrino telescopes when interacting with SM leptons. For all scenarios, we investigate the relevant parameter space, demonstrating that the future KM3NeT neutrino experiment will play a dominant role in constraining dark matter models, complementary to direct and indirect detection, especially in the case of the $L_{\mu-\tau}$ model.

The chapter is organized as follows. In Sec. 2.2, we delineate the main features of a neutrino flux originated by astrophysical sources and by decaying and annihilating DM particles. Section 2.3 describes how the neutrino sky map is computed for the null hypothesis (atmospheric background plus an astrophysical power-law component) and for the signal hypothesis (atmospheric background, an astrophysical power-law and DM components) that we want to test. In Sec. 2.4, we discuss the angular power spectrum analysis based on Monte Carlo simulations of the neutrino sky map. In Sec. 2.5, we report the current constraints and future sensitivity for DM lifetime and cross-section, while in Sec. 2.6, we discuss the dependence of the results on different astrophysical and DM models. Moreover, in Sec. 2.7 we discuss the analysis for lower energies with KM3NeT, where we consider model-independent bounds in Sec. 2.7.1 as well as model-dependent bounds in Sec. 2.7.4. Finally, in Sec. 2.8, we draw our
2.2 Neutrino flux

The neutrino flux observed with IceCube is typically explained in terms of the atmospheric neutrino background and an astrophysical power-law component. The former describes the neutrinos produced in the atmosphere through the interactions of cosmic rays, while the latter comes from a population of diffuse unresolved astrophysical sources. We consider only conventional atmospheric neutrinos, which are produced by decays of pions and kaons. Even though they are subdominant for $E_\nu > 60$ TeV (lower energy threshold considered in this analysis), we include these in our sky maps by adopting the flux model from Honda et al. (2015); Feyereisen et al. (2017). Furthermore, there might be a contribution coming from decaying or annihilating DM particles. In the following two subsections, we discuss the astrophysical and DM components, respectively.

2.2.1 Astrophysical power-law component

For the astrophysical component, we adopt an isotropic neutrino flux parameterized by a single power-law, having the following form:

$$\frac{d\Phi^{\text{astro}}_{\nu_\alpha + \bar{\nu}_\alpha}}{dE_\nu \, d\Omega} = \Phi_0 \left( \frac{E_\nu}{100 \text{ TeV}} \right)^{-\gamma},$$  \hspace{1cm} (2.1)

where $\Phi_0$ is the normalization of the astrophysical neutrino flux per neutrino flavor $\alpha$ at 100 TeV (in units of $10^{-18}$ GeV$^{-1}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$), and $\gamma$ is the spectral index. The parameters for the normalization and the spectral index are taken from the latest best-fits by IceCube for the two data samples of through-going (Stettner 2019) and HESE (Schneider 2019) events. In particular, we have $\gamma^{\text{TG}} = 2.28^{+0.08}_{-0.09}$ and $\gamma^{\text{HESE}} = 2.89^{+0.20}_{-0.19}$, and $\Phi_0^{\text{TG}} = 1.44^{+0.25}_{-0.24}$ and $\Phi_0^{\text{HESE}} = 2.15^{+0.49}_{-0.15}$.

2.2.2 Dark matter signal

High-energy neutrinos can be produced by DM particles through their decays or annihilations. The corresponding differential neutrino flux is the sum of the galactic (gal.) contribution from the Milky-Way halo and the extragalactic (ext.gal.) component:

$$\frac{d\Phi^{\text{DM}}_{\nu_\alpha + \bar{\nu}_\alpha}}{dE_\nu \, d\Omega} = \sum_\beta P_{\alpha\beta} \left[ \frac{d\Phi^{\text{gal.}}_{\nu_\beta + \bar{\nu}_\beta}}{dE_\nu \, d\Omega} + \frac{d\Phi^{\text{ext.gal.}}_{\nu_\beta + \bar{\nu}_\beta}}{dE_\nu \, d\Omega} \right],$$  \hspace{1cm} (2.2)

where the quantities $P_{\alpha\beta}$ take into account the neutrino flavour oscillations during the propagation from the source to the Earth. Using the mixing angles obtained by
the recent global neutrino fit (Capozzi et al. 2018, 2020), we get

\[ P_{ee} = 0.551, \quad P_{e\mu} = 0.191, \quad P_{e\tau} = 0.258, \quad P_{\mu\mu} = 0.427, \quad P_{\mu\tau} = 0.383, \quad P_{\tau\tau} = 0.359. \] (2.3)

The two contributions in Eq. (2.2) take different expressions in case of a decaying (dec.) or annihilating (ann.) DM signal, as described in Eq. 1.13 for the galactic contribution. For the extra-galactic decaying scenario, we have

\[ \left. \frac{d\Phi_{\nu_\beta+\bar{\nu}_\beta}}{dE_\nu d\Omega} \right|_{\text{dec.}} = \frac{\Omega_{\text{DM}} \rho_c}{4\pi m_{\text{DM}} \tau_{\text{DM}}} \int_0^\infty dz \frac{1}{H(z)} \left. \frac{dN_\beta}{dE'_\nu} \right|_{E'_\nu=E_\nu(1+z)}, \] (2.4)

where \( \rho_c = 5.5 \times 10^{-6} \text{ GeV cm}^{-3} \) is the critical energy density and \( H(z) \) is the Hubble expansion rate as measured by Planck (Ade et al. 2016). Lastly, both galactic and extra-galactic fluxes depend on the energy spectrum \( dN_\beta/dE_\nu \) of \( \beta \)-flavor neutrinos produced by DM particles. This quantity is obtained by taking the spectra from the PPPC package (Cirelli et al. 2011) and following the scaling procedure for DM masses larger than 100 TeV reported in Chianese et al. (2017b). As discussed in Chianese et al. (2019), such a procedure provides energy spectra compatible with the ones computed using PYTHIA (Sjöstrand et al. 2015).

In the case of annihilating DM, the extragalactic component is given by

\[ \left. \frac{d\Phi_{\nu_\beta+\bar{\nu}_\beta}}{dE_\nu d\Omega} \right|_{\text{ann.}} = \frac{1}{2} \frac{\Omega_{\text{DM}} \rho_c}{4\pi m_{\text{DM}}^2} \int_0^\infty dz \frac{B(z)}{H(z)} \left(1+z\right)^3 \left. \frac{dN_\beta}{dE'_\nu} \right|_{E'_\nu=E_\nu(1+z)} \] (2.5)

where the redshift integral contains the boost factor (or clumpiness factor) \( B(z) \), which accommodates the impact of the amount of DM substructures in the intergalactic medium (see Ando et al. (2019a) for a recent review) as well as the halo mass function (Sheth & Tormen 1999; Sheth et al. 2001). Here, we do not consider the effect of the presence of DM subhalos in our galaxy (see for example Zavala (2014)).

In the case of DM annihilation, in order to accommodate uncertainties on the DM substructures, we examine three different models for the cosmological boost factor \( B(z) \): the semi-analytical model described in Hiroshima et al. (2018a) (hereafter dubbed as HAI), the “Macciò” model (Macciò et al. 2008) that is based on an earlier phenomenological model (Bullock et al. 2001), and “power-law” model (Neto et al. 2007; Macciò et al. 2008) that is obtained by extrapolating the results for the concentration parameter from ab-initio N-body simulations, by taking a minimum halo mass of \( 10^{-6}M_\odot \) (Cirelli et al. 2011). We note that the simple power-law extrapolation of the concentration-mass relation, which yields significant overestimate of the neutrino flux, is no longer considered realistic. Figure B shows the boost factor as a function of the redshift \( z \) for the three models. It is worth noticing that the HAI model is valid until redshift \( z \approx 7 \) and we simply take \( B_{\text{HAI}}(z) = 1 \) for \( z \gtrsim 7 \). It is worth observing
that regions at higher redshift provide in general a subdominant contribution to the total DM component. In particular, due to the redshift of the neutrino energy, the regions for $z \gtrsim 7$ would marginally contribute to the neutrino spectrum at neutrino energies $E_\nu \lesssim \mathcal{O}(100 \text{ TeV})$ only in case of dark matter masses $m_{DM} \gtrsim 1 \text{ PeV}$. We have checked that for all the different boost factor models this contribution is typically subdominant when analyzing the neutrino sky above 60 TeV, which is the lower energy threshold in the present analysis (see the discussion below).

![Image of dark matter boost factors as a function of the redshift for different models considered in this work.](image)

**Figure 2.1:** Dark matter boost factors as a function of the redshift for different models considered in this work.

### 2.3 High-energy neutrino sky map

We simulate the neutrino sky map above 60 TeV under two different assumptions:

- **Null hypothesis:** in addition to the conventional atmospheric neutrino background (atm), we consider an isotropic astrophysical component only

  $$
  \frac{d\Phi_{\text{null}}}{dE_\nu d\Omega} = \frac{d\Phi_{\text{atm}}}{dE_\nu d\Omega} + \frac{d\Phi_{\text{HESE astro}}}{dE_\nu d\Omega},
  $$

  where we use the HESE best-fit for the astrophysical component.

- **Signal hypothesis:** we include a DM component so having

  $$
  \frac{d\Phi_{\text{signal}}}{dE_\nu d\Omega} = \frac{d\Phi_{\text{atm}}}{dE_\nu d\Omega} + \frac{d\Phi_{\text{TG astro}}}{dE_\nu d\Omega} + \frac{d\Phi_{\text{DM}}}{dE_\nu d\Omega}.
  $$
In this case, the astrophysical power-law is fixed by the TG data sample. Hence, the neutrino flux originated by DM is the additional component required to alleviate the tension between HESE and TG data sets. Then, we test various parameters for decaying and annihilating DM signals.

For each flux component, the expected number of observed neutrino events in a region of the sky \( \Delta\Omega \) identified by the position \( \theta \) (declination) and \( \phi \) (right ascension) is derived as follows

\[
N_\nu(\theta,\phi) = \int_{\Delta\Omega} d\Omega \int_{E_{\text{th}}}^{E_{\text{max}}} dE_\nu \sum_\alpha f_\alpha \frac{d\Phi_{\nu_\alpha+\bar{\nu}_\alpha}}{dE_\nu} \mathcal{E}_\alpha(E_\nu, \Omega) \text{vis}(\Omega). \tag{2.8}
\]

Here, \( \mathcal{E}_\alpha(E_\nu, \Omega) = T_{\text{obs}} A_{\text{eff},\alpha}(E_\nu, \Omega) \) is the detector’s exposure for neutrino flavor \( \alpha \) with \( T_{\text{obs}} \) and \( A_{\text{eff},\alpha} \) being the observation time and the detector’s effective area, respectively. The quantity \( \text{vis}(\Omega) \) is the visibility function quantifying the fraction of the year during which a point in the sky can be observed by the telescope. In general, it is a non-trivial function that depends on the Earth rotation and the veto technique of the telescope to suppress the atmospheric background. In the case of IceCube, we consider the HESE effective area (Aartsen et al. 2013) and \( \text{vis}^{\text{IC}}(\Omega) = 1 \) thanks to the muon self-veto (Gaisser et al. 2014; Argüelles et al. 2018). The same is assumed for IceCube-Gen2 for which we take its effective area to simply be ten times larger than the HESE one. For KM3NeT, we use the exposure and the visibility function reported in Adrian-Martínez et al. (2016b), and account for the Earth’s absorption using the code \( \nu\text{FATE} \) (Vincent et al. 2017). In Eq. (2.8), the factor \( f_\alpha \) takes into account the fraction of neutrinos producing an event with shower or track topology, so that \( f^{\text{shower}}_\alpha + f^{\text{track}}_\alpha = 1 \). For the sake of simplicity, we assume that electron and tau neutrinos produce only shower events, and therefore \( f^{\text{shower}}_\tau \simeq f^{\text{shower}}_e \approx 1 \). On the other hand, only a fraction \( f^{\text{track}}_\nu = 0.8 \) of muon neutrinos provides track-like events, according to the probability of having charged current interaction, i.e. \( \sigma_{\text{CC}}/(\sigma_{\text{NC}} + \sigma_{\text{CC}}) \approx 0.8 \) (Gandhi et al. 1998). In order to reduce the background contamination (penetrating atmospheric muons and conventional atmospheric neutrinos) in IceCube, we consider only shower-like events. This implies that \( f^{\text{IC}}_\tau = f^{\text{IC}}_e = 1 \) and \( f^{\text{IC}}_\mu = 0.2 \). In the case of KM3NeT, we instead examine only through-going track events for which \( f^{\text{KM3NeT}}_\tau = f^{\text{KM3NeT}}_e = 0 \) and \( f^{\text{KM3NeT}}_\mu = 0.8 \). Furthermore, for both telescopes, we set a lower energy threshold of \( E_{\text{th}} = 60 \text{ TeV} \) in order to further suppress the background events, and an upper limit corresponding to the DM mass with \( E_{\text{max}} = m_{\text{DM}}/2 \) for decaying DM and \( E_{\text{max}} = m_{\text{DM}} \) for annihilating DM scenarios. Such an upper energy threshold corresponds to the maximum energy available for neutrinos produced by DM particles. It is worth noticing that these cuts on neutrino energies and the event topology selection for IceCube and KM3NeT considered in the present analysis are not aimed at providing the optimal strategy for data-analysis. Instead, we aim at highlighting the potentiality of analyzing the angular
power spectrum of the neutrino sky with both the telescopes. Moreover, we stress that IceCube and KM3NeT are expected to provide different constraints on the dark matter parameters mainly due to the different sensitivity to the galactic center.

The simulated sky maps are therefore given by the sum of the following contributions:

$$N_{\text{tot}}(\theta, \phi) = N_{\text{atm}} + N_{\text{astro}} + N_{\text{DM}},$$  \hspace{1cm} (2.9)

where the DM events are further obtained by summing the galactic and extragalactic contributions

$$N_{\text{DM}} = N_{\text{gal}}^{\text{DM}} + N_{\text{ext.gal}}^{\text{DM}}. \hspace{1cm} (2.10)$$

In the present analysis, we assume that the level of anisotropy in the neutrino flux is set only by the galactic DM component, while the other contributions are considered to be statistically isotropic. This is not true for the atmospheric flux measured by IceCube since the muon veto of the experiment highly suppresses the down-going atmospheric neutrinos. However, in our settings, above a neutrino energy of 60 TeV, we expect less than 1 atmospheric neutrino event per year with a shower-like topology. This explains why we consider only shower events when analyzing IceCube. For KM3NeT, since the contamination of the atmospheric neutrino background above 60 TeV is still expected to be small, the null hypothesis flux can be statistically approximated to be isotropic.

Hence, the ratio between anisotropic and isotropic number of neutrino events depends on DM parameters like for instance the density profile, boost factor and DM lifetime or cross-section. We thus aim to constrain DM parameters by testing our two-component model (signal hypothesis) with respect to an isotropic astrophysical model (null hypothesis). Figure 2.2 illustrates the differences in angular patterns for the null hypothesis (left) and for two signal hypotheses with decaying (middle) and annihilating (right) DM component. These sky maps corresponds to one Monte Carlo realization with 10 years of IceCube-Gen2 exposure. The number of galactic neutrino events coming from annihilating DM is related to the halo density as $N_{\text{gal}}^{\text{DM}} \propto \rho^2$, while $N_{\text{DM}}^{\text{gal}} \propto \rho$ for decaying DM. This produces different amount of anisotropy as can be seen in the figure. In both cases, we have considered the NFW halo density and the semi-analytical HAI model for the boost factor. We will be examining these angular patterns with an angular power spectrum analysis, as described below.

## 2.4 Angular Power Spectrum analysis

The angular power spectrum (APS) shows to be a powerful probe to asses anisotropies on the neutrino sky (Dekker & Ando 2019). The fluctuations on the neutrino sky map
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Figure 2.2: Neutrino sky maps under different flux hypotheses after 10 years of observation in IceCube-Gen2. The left panel shows the angular distribution of neutrino events under the null hypothesis of a nearly isotropic flux (atmospheric and astrophysical power-law components). The middle and right panels display the sky maps for the signal hypothesis with an additional component coming from decaying and annihilating DM particles, respectively.
2.4 Angular Power Spectrum analysis

are found by expanding the map into spherical harmonics:

\[ N(\theta, \phi) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta, \phi), \quad (2.11) \]

where \( N(\theta, \phi) \) is the neutrino event at declination \( (\theta) \) and right ascension \( (\phi) \), and \( Y_{\ell m}(\theta, \phi) \) are the spherical harmonic functions. The APS is then given by averaging the expansion coefficients over the sky:

\[ C'_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} \left| a_{\ell m} \right|^2. \quad (2.12) \]

We compute the APS using the numerical function anafast from the software package HEALPix (Gorski et al. 2005). Since we are only interested in anisotropic effects, we want to remove any information on the number of events. We therefore remove the monopole and normalize the remaining coefficients as

\[ C_\ell = \frac{C'_\ell}{N_{\text{tot}}^2} \quad \text{for} \quad \ell > 0, \quad (2.13) \]

where \( N_{\text{tot}} \) is the total number of neutrino events. The first multipole moments show larger angular power due to the anisotropy of events coming from the galactic center, which is detectable on top of the isotropic distribution. We calculate the APS up to \( \ell_{\text{max}} = 9 \) for IceCube, IceCube-Gen2 and KM3NeT maps, which corresponds to the typical angular resolution of IceCube for HESE events, 11° (Aartsen et al. 2013, 2014).

Even though KM3NeT has a better angular resolution of 0.07°, including larger multipole moments will not improve our analysis since only the first multipole moments are of interest for our work. Indeed, the multipole moments with \( \ell > 9 \) related to the smooth and extended dark matter galactic component are not substantially different from the ones corresponding to an isotropic sky.

We perform Monte Carlo simulations for decaying and annihilating dark matter models and range the lifetime between \( \tau_{\text{DM}} = [10^{26}, 10^{31}] \) s in the case of decaying dark matter and the cross-section between \( \langle \sigma v \rangle = [10^{-26}, 10^{-20}] \) cm\(^3\)s\(^{-1}\) for annihilating dark matter, both in steps of \( \log(0.2) \). Additionally, we simulate purely isotropic astrophysical + atmospheric sky maps for the null hypothesis. Each case is simulated \( 10^5 \) times for IceCube, IceCube-Gen2 and KM3NeT exposures and we calculate their APS. In order to have a statistical measure for the goodness of the models, we apply the following \( \chi^2 \),

\[ \chi^2(C_\ell) = \sum_{\ell \ell'} (C_\ell - C^\text{mean}_\ell) (\text{Cov}_{\ell\ell'})^{-1} (C_{\ell'} - C^\text{mean}_{\ell'}) , \quad (2.14) \]

where \( C_\ell \) is the APS of one simulation, \( C^\text{mean}_\ell \) is the mean value and \( \text{Cov}_{\ell\ell'} \) is the covariance matrix, where \( C^\text{mean}_\ell \) and \( \text{Cov}_{\ell\ell'} \) are obtained from a complete set of simulation of the signal hypothesis. For each characterization of the model, we calculate
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Figure 2.3: Results from simulated sky maps for different observations. The $p$-value bands as a function of the expected total DM neutrino events, for the signal hypothesis with annihilating (blue) and decaying (brown) DM particles into $\tau^+ \tau^-$, assuming NFW halo profile and HAI boost factor. The DM mass is taken to be 200 and 400 TeV, respectively. The panels from left to right correspond to 6-year IceCube, 10-year KM3NeT and 10-year IceCube-Gen2 exposures, respectively. The dark and light colors refer to the 68% and 95% Monte Carlo realizations of the null-hypothesis sky map. The horizontal dashed line highlights the exclusion limit of $p = 0.05$. In the left panel, the solid lines show the constraints from current 6-years IceCube HESE data.

the probability density function (PDF) of $\chi^2$, $P(\chi^2|\Theta)$ with $\Theta$ the parameters of the DM component. We then compute $\chi^2_{\text{data}} \equiv \chi^2(C^\text{data}_\ell)$ from the observed neutrino sky to obtain the probability of having the same or more extreme values of $\chi^2$ by the following $p$-value,

$$p = \int_{\chi^2_{\text{data}}}^{\infty} d\chi^2 P(\chi^2|\Theta). \quad (2.15)$$

Models are constrained at 95% confidence level (CL), which is equivalent to $p \leq 0.05$. For the forecast we use the isotropic best-fit model from Schneider (2019) (null hypothesis) as data for $\chi^2_{\text{data}} \equiv \chi^2(C^\text{data}_\ell)$, which we simulate $10^5$ times as well. Instead of a single $p$-value, we therefore get a distribution of $10^5 p$-values, from which we consider the 68% and 95% contour bands symmetrically distributed around the mean.

2.5 Results

We analyze the APS of the simulated sky maps obtained under the null hypothesis and the signal hypothesis for decaying and annihilating DM particles. In this section, we assume the NFW profile and the HAI boost factor as benchmark scenario. In Fig. 2.3 we report the results for current data with 6-year exposure time in IceCube (left panel), and future observations with 10 years of data-taking with KM3NeT (middle panel) and IceCube-Gen2 (right panel). The bands cover different Monte
Carlo realizations of the null-hypothesis sky map used to test the DM scenarios of annihilation (blue) and decay (brown) into the leptonic final state of $\tau^+\tau^-$ with a DM mass of 200 and 400 TeV, respectively. In particular, we show the 68% (dark colors) and 95% (light colors) contour bands from Monte Carlo simulations. In the left panel, we report the APS fits of the 6-year IceCube HESE observations, shown by the solid lines.\(^1\) The 6-year HESE data consist of 33 neutrino events in the energy range 60–200 TeV, where 200 TeV corresponds to the maximum energy of neutrinos produced by DM particles. The horizontal black dashed line represents the exclusion limit of $p = 0.05$ below which the two-component hypothesis is rejected. As can been seen in the plots, the APS analysis constrains the total number of neutrino events related to the DM signal: a larger DM contribution would produce a higher anisotropy towards the galactic center in contrast with the null hypothesis. On the other hand, when the number of DM neutrino events is small, the signal hypothesis becomes indistinguishable from the null hypothesis due to a negligible DM contribution. In this case, the distribution of $p$-values simply corresponds to the Monte Carlo Poisson noise of the $10^5$ null-hypothesis realizations. Such a behaviour can be seen in all the plots. In all the cases, when decreasing the number of DM neutrino events, the $p$-values move from being very small due to the strong disagreement between the null and the signal hypotheses to being dominated by the Monte Carlo Poisson noise.\(^2\) Therefore, in order to provide conservative constraints and future sensitivity on the total DM events at 95% CL ($p$-value smaller than 0.05), we consider the upper 95% bound and the mean of the $p$-value distribution obtained by the Monte Carlo simulations of the null-hypothesis.

It is worth observing that the constraints on the annihilating scenario are stronger than the ones for decaying one. This is indeed expected due to the more concentrated contribution from the galactic halo in case of annihilating DM particles (see Fig. 2.2). However, as discussed in Sec. 2.6, the constraints on the total DM events depend on the models for the halo profile and the boost factor, since they set the relative contribution between galactic and extragalactic DM fluxes. On the other hand, the limits presented here are slightly dependent on the DM mass and almost independent of the annihilating/decaying channel. Indeed, the whole analysis is not very sensitive to the energy spectrum of neutrinos since the sky map is integrated over neutrino energy.

The upper bounds on the total DM neutrino events are translated into constraints on the DM lifetime (left panel) and cross-section (right panel) in Fig. 2.4. In this figure, we compare the sensitivity to DM parameters of IceCube (orange),

\(^1\)We perform the APS analysis on the 6-year IceCube HESE data because the angular coordinates of the events in the updated 7.5-year data-set are not yet public.

\(^2\)Note that the null-hypothesis (Eq. (2.6) and the signal hypothesis (Eq. (2.7)) are not nested, according to the different assumption on the astrophysical flux component.
Dark matter signals from the galactic halo with neutrino telescopes

Figure 2.4: \( p \)–values from simulated sky maps after 10-year observations with different neutrino telescopes. The 95% bands of \( p \)–values from Monte Carlo simulations as a function of DM lifetime (left) and cross-section (right) for \( \tau^+ \tau^- \) final state and DM mass of 400 and 200 TeV, respectively. The different bands represent 10-year observations with IceCube HESE (orange), IceCube-Gen2 HESE (blue) and KM3NeT through-going muon neutrinos (green) exposures. The dot-dashed lines inside the 95% bands show the median \( p \)-values obtained from simulations. In the right panel, the vertical black solid line is the unitarity bound on cross-section.

KM3NeT (green) and IceCube-Gen2 (blue) after 10 years of observations. Remarkably, KM3NeT is found to be more sensitive to the DM models considered, so providing stronger constraints with respect to IceCube and IceCube-Gen2. This is indeed expected thanks to the KM3NeT geographical position that is more suitable to observe the galactic center via through-going neutrinos. On the other hand, the observation of the galactic center with IceCube and its future upgrade IceCube-Gen2 is limited by a smaller effective area due to the requirement of having down-going contained events. However, this is not enough to reach the unitarity limit (vertical solid line in Fig. 2.4) on the DM cross-section implying \( \langle \sigma v \rangle \lesssim 4 \times 10^{-24} \text{ cm}^3\text{s}^{-1} \) for \( m_{DM} = 200 \text{ TeV} \) (Griest & Kamionkowski 1990b). Finally, in the figure, we also report the current constraints from the 6-year IceCube HESE data with the solid black lines. In particular, we have \( \tau > 1.9 \times 10^{27} \text{s} \) and \( \langle \sigma v \rangle < 1.17 \times 10^{-22} \text{ cm}^3\text{s}^{-1} \) corresponding to \( p \)–values smaller than 0.05.

The main results of the present analysis are reported in Figs. 2.5 and 2.6, where we show the future sensitivity of neutrino telescopes to decaying and annihilating DM models, respectively. We consider the channels into tau leptons (\( \tau^+ \tau^- \)) and top quarks (\( t\bar{t} \)) as representative of different neutrino energy spectrum of the DM signals. The current constraints deduced from 6-year IceCube data are shown by the solid black lines. Other bounds shown are: gamma-ray searches from the galactic halo by HAWC (Abeysekara et al. 2018) (grey solid lines), global gamma-rays constraints from Cohen et al. (2017) (grey dot-dashed lines), and the unitarity constraints on cross-section (Griest & Kamionkowski 1990b) (black dashed lines).
Figure 2.5: Future sensitivity to decaying dark matter models. Sensitivity at 95% CL to DM lifetime as a function of DM mass after 10-year exposures of IceCube (orange), KM3NeT (green) and IceCube-Gen2 (blue) experiments. The bands represent the median (dashed lines) and 95% (solid lines) conservative sensitivity from the Monte Carlo simulations. The current constraints from 6-year HESE data are shown with solid black lines. The left and right plots correspond to the $\tau^+\tau^-$ and $t\bar{t}$ channels, respectively. The black stars show the current best-fit of the DM component deduced by 7.5-year IceCube HESE data (Chianese et al. 2019). The gamma-ray constraints are represented by light grey lines: solid from HAWC galactic halo searches (Abeysekara et al. 2018) and dot-dashed from Cohen et al. (2017).
Figure 2.6: Future sensitivity to annihilating dark matter models. The plots are explained in the caption of Fig. 2.5. In addition, the dashed black lines mark the unitarity limit on DM cross-section.
2.6 Discussion

In the plots, the bands have been obtained by performing the APS analysis on simulated sky maps with different DM mass. They represent the sensitivity for an observed $p$-value of 0.05 from the median and upper 95% values on the total DM events from the Monte Carlo simulations. Both KM3NeT and IceCube-Gen2 will probe a much bigger parameter space of DM models. In particular, KM3NeT turns out to be more sensitive to DM models with a low DM mass, as also shown in Fig. 2.4. However, for DM masses larger than PeV, the sensitivity of KM3NeT is weaker than the one of IceCube-Gen2. This is due to two effects. At high energies, there is an enhancement in the expected number of shower events in IceCube thanks to the Glashow resonance of anti-electron neutrinos. This is not the case for KM3NeT, as it is based only on track-like events related to CC interactions of muon neutrinos. Moreover, KM3NeT will observe the galactic center through the Earth. While at low energies this is important to reduce the atmospheric (muon) background, at high energies the neutrino flux is reduced due to Earth absorption. On the other hand, the galactic center is observed by IceCube through down-going neutrinos that do not pass through the Earth.

Remarkably, KM3NeT and IceCube-Gen2 will probe a much bigger parameter space of DM models. In particular, they will be sensitive to the present 7.5-year HESE best-fit of the additional decaying DM component (Chianese et al. 2019), shown with black stars in Fig. 2.5. We emphasize that this result relies only on the angular information contained in the neutrino sky maps. This makes the APS analysis very robust against any potential degeneracies in the neutrino energy spectrum expected from astrophysical sources and DM particles. It is worth observing that for leptophilic channels the current best-fit of the DM component is not yet excluded by gamma-ray constraints.

2.6 Discussion

The results in the previous section have been obtained for benchmark models. However, other DM models can lead to different angular patterns and therefore lead to different exclusion limits. We thus discuss in detail how the sensitivity depends on DM properties like the channel, the DM mass, the galactic halo profile, and the boost factor using 10 years of IceCube-Gen2 exposure.

For the case of decaying DM scenario, as shown in Fig. 2.3, we have previously assumed $m_{\text{DM}} = 400$ TeV, $\text{DM} \rightarrow \tau^- \tau^+$, and the NFW profile for the galactic halo. Figure 2.7 shows the 95% contour $p$-value bands, where we compare in each panel the results for the benchmark parameters together with a parameter that we want to test. The left panel shows two different DM masses with $m_{\text{DM}} = 400$ TeV and $m_{\text{DM}} = 4$ PeV, the middle panel the two channels of $\text{DM} \rightarrow \tau^- \tau^+$ and $\text{DM} \rightarrow t\bar{t}$, and the right panel the isothermal density profile together with the NFW profile. We
find that the exclusion limits on the total DM events do not significantly change in all the cases. However, when plotted against the lifetime, the constraints change. For instance, the $\tau$–channel produces more events than the $t$–channel, and has therefore stronger constraints on the lifetime as shown in Fig. 2.5. This allows one to set almost model-independent limits on the total DM events and then translate them into constraints on DM lifetime for different DM models. Concerning the DM halo (right panel), the agreement between NFW and Isothermal profiles is a result of similar ratio between galactic and extra-galactic DM events, whithin the angular resolution considered in this analysis.

We perform the same tests for annihilating DM scenario for which we previously assumed the following benchmark model: $m_{DM} = 200$ TeV, $DM \rightarrow \tau^- \tau^+$, NFW halo profile, and the HAI boost factor (Hiroshima et al. 2018a). Figure 2.8 shows
2.6 Discussion

Figure 2.9: Uncertainty test for the astrophysical component We test the robustness of our analysis against the 1σ upper and lower uncertainty of the astrophysical power-law obtained from the TG data sample. Shown are the 95% contour bands of $p$–values from Monte Carlo simulations using benchmark model of decaying DM.

the 95% contour bands of the $p$–value results, where we vary the DM parameters. As before, the sensitivity on the total DM events does not significantly depends on the channel, while considering larger DM masses reduces the limits by roughly 18% (see for example the left panel). On the other hand, considering an isothermal density profile instead of the NFW one makes the constraints 70% weaker, as shown in the middle panel. This is due to the NFW density profile being denser in the inner center than the isothermal profile (see Fig. B), and to the fact that in the case of annihilation the number of neutrino events scales stronger with the density than for decaying DM. Finally, the right panel shows the impact on the constraints for three different boost factors, namely the HAI, power-law and Macciò models (see Fig. B). The boost factor is very important in setting constraints from angular information, since the ratio between galactic and extragalactic DM events strongly depends on it. In particular, the constraints with the power-law boost factor are weaker by a factor of 2.4 (140%), while the ones for the Macciò model are stronger by a factor of 0.8 (20%). It is worth observing that this difference has a direct impact on the sensitivity reported in Fig. 2.6, which can be simply rescaled for different DM models.

Finally, in Fig. 2.9 we discuss the impact of the statistical uncertainty affecting the best-fit for the astrophysical power-law from the TG data sample. In particular, we test if our results are robust for the 1σ statistical uncertainty on the normalization and spectral index of the observed spectrum and show here the $p$–value result for the
benchmark model for decaying DM particles. The best-fit is shown as the grey shaded area delimited by dashed lines, and in blue and orange are the $1\sigma$ upper and lower limit. As can be clearly seen, in all the cases the corresponding bounds on the total DM events are the same.

## 2.7 Low energy analysis with KM3NeT

As KM3NeT is especially sensitive to DM models with a low mass, we analyse in this section a DM mass between 200 GeV and 100 TeV. Here, we simulate neutrino skymaps with expected dark matter signal and background events for 10 years of data-taking period of the KM3NeT-ARCA site, dedicated to detection of high energy neutrino events as described in Adrián-Martínez et al. (2016), considering only through-going track events in order to reduce the atmospheric muon background. The difference with the sky maps discussed in Sec. 2.3 is that we neglect any astrophysical contribution to the total skymaps as the astrophysical flux is subdominant with respect to the atmospheric neutrino flux in the energy range we are interested in.

In order to gain a larger sensitivity, we consider only a small energy range around the peak of the dark matter spectrum with $E_\nu = [10^{-10} m_{DM}, m_{DM}]$. The neutrino lines show a sharper peak with respect to other channels, therefore we consider a narrower energy range for this case with $E_\nu = [10^{-2} m_{DM}, m_{DM}]$.

The largest contributions to the APS come from the first multipole moments. Therefore, we analyse the APS with maximum moment $\ell_{\text{max}} = 8$. We do this despite the fact that KM3NeT’s angular resolution allows one to go higher. For each dark matter model, we perform $10^5$ Monte Carlo simulations, vary the cross-sections between $\langle \sigma v \rangle = [10^{-25}, 10^{-22}] \text{ cm}^3\text{s}^{-1}$ in steps of $\Delta \log_{10}\langle \sigma v \rangle = 0.2$, and calculate the corresponding APS. Additionally, we generate mock data sets by performing $10^5$ Monte Carlo simulations under the background-only hypothesis and perform the analysis as described in Sec. 2.4. The expected upper-limit on dark matter annihilation cross-section for a given channel at a certain mass value is then obtained at 90% confidence level (CL) at $p \leq 0.10$.

### 2.7.1 Model-independent bounds

We present the results obtained through the angular power spectrum forecast analysis as described above. In Fig. 2.10, we report the future KM3NeT sensitivity at 90% CL with 10-year exposure to WIMP dark matter annihilation cross-section for different channels. For the channels involving neutrinos in the final states, we assume equipartition among neutrino flavours. Nevertheless, neutrino channels with a specific flavour at the production result in very similar bounds due to neutrino oscillations during the propagation to the Earth. In the plots, the bands have been obtained by...
analyzing the angular power spectrum of $10^5$ simulated neutrino skymaps for each value of the dark matter mass considered. In particular, the solid and dashed lines represent the median and conservative $2\sigma$ upper bounds obtained from the Monte Carlo simulations at 90% CL, assuming the NFW halo profile for the galactic dark matter distribution. The grey region is excluded by the requirement of unitarity of the dark matter annihilation cross-section (Griest & Kamionkowski 1990b). As can be seen in the plots, the limits for the electron and bottom quark channels stop at $m_{\text{DM}} = 1$ TeV and $m_{\text{DM}} = 500$ GeV, respectively. Below such masses, the detection efficiency is very suppressed for both channels. In case of the electron channel, neutrinos are only produced through the electroweak radiation which are not very efficient below TeV energies producing detectable neutrinos in our study. For dark matter masses below 600 GeV, most of the neutrinos, produced by the annihilation into bottom quarks, have an energy smaller than 100 GeV, which is below the sensitivity of the KM3NeT-ARCA detector. This is why the upper limits break down at that dark matter mass.

In Fig. 2.11 we graphically quantify the systematic uncertainty affecting our constraints (blue band) according to different choices for the dark matter distribution in our galaxy. In particular, we show the median sensitivity at 90% CL for the two extreme cases of NFW (solid blue lines) and Burkert (dot-dashed blue lines) profiles for
two annihilation channels. The plots correspond to two different annihilation channels of dark matter particles: neutrino lines (left plot) and charged muons (right plot). We also report the existing upper limits placed by dark matter searches in neutrino telescopes: 3-year IceCube (Aartsen et al. 2017b) (red band), 11-year ANTARES (Albert et al. 2020) (green band), and 1-year IceCube with a similar multipole analysis study (Aartsen et al. 2015b) (black band) simply denoted as “IceCube APS” for the sake of brevity. For consistent comparison, we have properly scaled these constraints to our set of dark matter halo parameters.

One can observe that the APS method is very stable over different halo profiles. On average the Burkert distribution weakens the limits by only $\sim 40\%$ with respect to NFW. For example, taking $m_{DM} = 10^4$ GeV, annihilation cross-section into neutrinos will be constrained to be below $1.21 \times 10^{-24}$ cm$^3$/s and $8.52 \times 10^{-25}$ cm$^3$/s for Burkert and NFW respectively. Comparing this result to studies which do not use the APS method such as ANTARES (Albert et al. 2020), there is a much greater variation due to the choice of halo profile. Moreover, if we compare our results to that of another APS study, such as the one performed for IceCube in Aartsen et al. (2015b), we see a projected improvement of over an order of magnitude. Obtaining these robust limits will have significant implications on the particle physics interpretations. In the next section we elaborate on this.

### 2.7.2 Dark Matter Models for Neutrino Telescopes

While in the previous sections we have presented model-independent bounds for the neutrino telescope, in this section we provide interpretation of these bounds in terms of selected minimal dark matter models, which have the advantage that KM3NeT will give the most competitive insight for. Additionally, interpretation of bounds allows for a complementary analysis that compares the sensitivity of different dark matter probes.

From the model building perspective, our starting point is the simplified model framework, which has been investigated recently at the LHC (Abercrombie et al. 2020; Boveia et al. 2020; Abdallah et al. 2015; Kahlhoefer 2017; Arcadi et al. 2018a; Arina 2018). This entails making minimal additions to the SM by way of couplings and particles in order to incorporate a dark matter particle candidate. It allows for the exploration of scenarios in a rather model-independent way and eases the comparison of theoretical predictions with the various experiments. Such models can be categorised in terms of $s$-channel and $t$-channel, which from a structural point of view are very different.

The $s$-channel models feature a new boson which mediates between two dark matter and two SM particles, hence it is even under the dark group that protects the dark matter particle from decaying. The new boson is also a singlet under the SM gauge group. As a consequence, this mediator can be lighter or heavier than the dark
2.7 Low energy analysis with KM3NeT

Figure 2.11: **Left:** Present and future limits placed by neutrino telescopes on the dark matter annihilation cross-section to neutrinos. The bands represent the uncertainty related to different galactic dark matter profile: the lower (upper) edges refer to NFW (Burkert) density profile. The blue region is the median sensitivity at 90% CL after 10-year exposure of KM3NeT obtained through the angular power spectrum (APS) method in case of NFW (solid lines) and Burkert (dot-dashed lines) profiles. The other bands corresponds to the dark matter search analyses: 3-year IceCube (Aartsen et al. 2017b) (red band), 11-year ANTARES (Albert et al. 2020) (green band), and 1-year IceCube with a similar multipole study (Aartsen et al. 2015b) (black band). The grey region in the top-right corner is excluded by unitarity (see text). **Right:** Same as left for dark matter annihilation into muons.

Alternatively, \( t \)-channel models feature a new interaction vertex coupling directly one dark matter particle with a new mediator and a SM particle. This requires a discrete \( Z_2 \) and continuous global \( U(1) \) symmetries to stabilise the real and complex dark matter candidate respectively. It also implies that the mediator is charged under the dark group, hence can only be heavier than the dark matter particle.

More specifically, among the various realizations of \( s \)- and \( t \)-channel models, we select models that share at least these two properties:

- **Leptophilic models:** The mediator and the dark matter do not couple at tree level to quarks (nor to the Higgs and to electroweak gauge bosons) by construction, but feature purely leptonic final states, preferably neutrinos, which are the most promising for neutrino telescopes when compared with other dark matter searches. In particular, annihilation of dark matter can produce sizable neutrino lines or neutrino box signals at tree level, with branching ratio close or equal to the one into charged leptons, when latter annihilation channels can not be suppressed.

- **\( s \)-wave annihilation:** We require that the dark matter velocity/thermally av-
eraged annihilation cross-section $\sigma_v$ into SM particles is independent of the relative dark matter velocity. This means that at present time $\sigma_v$ can be potentially large in galactic halos (characterized by $v \simeq (10^{-5} - 10^{-3}) c$) and in the reach of KM3NeT. We do not focus however on thermal dark matter scenarios but consider the whole parameter space, remaining agnostic on the mechanism that provides 100% of the relic density $\Omega h^2$ measured by Planck (Aghanim et al. 2020). Notice that the values to which KM3NeT is sensitive, as obtained in previous section with APS ($\sigma_v \simeq 10^{-24} \text{cm}^3/\text{s}$), denote the region of underabundant dark matter assuming standard freeze-out, because $\Omega h^2 \propto \sigma_v^{-1}$. However we will show that for certain models, KM3NeT will be able to probe thermal values obtained with the standard freeze-out mechanism.

The latter requirement severely restricts the possibilities in term of $s$- and $t$-channel models. Taking the dark matter to be a singlet Dirac Fermion ($\chi$) the only viable choice for the mediator in case of $s$-channel models is spin 1 ($Z'$ henceforth), while for $t$-channel is a scalar mediator ($\varphi$). The relevant annihilation diagrams are shown in Fig. 2.12. These models are a subset of those studied in Lindner et al. (2010); El Aisati et al. (2017) in the context of neutrino line signals. $m_\chi \sim 550 \text{ GeV}$, Fermi limits from the charged lepton channel (blue line) dominate.

Reference El Aisati et al. (2017) exhibited well the difficulty a model builder has when trying to optimise the prospects of neutrino telescopes. This is especially true when one is attempting to work with a simple extension of the SM that is theoretically well-motivated. In the next sections we will build on El Aisati et al. (2017) by considering specific coupling configurations and adding vital direct detection constraints. First, we discuss all the experimental constraints (indirect detection, direct detection, collider searches and cosmological bounds) we consider in conjunction with the potential of the analysis technique which is described in previous section.
2.7.3 Complementary constraints to neutrino telescopes

The models we analyze are implemented in FeynRules (Alloul et al. 2014) and we use the corresponding UFO files to compute $\sigma_v$ with MadDM (Ambrogi et al. 2019) for both the thermally averaged cross-section for relic density and the annihilation cross-section at present time, which actually coincide at leading order as we consider s-wave annihilation. Notice that the predicted flux of SM particles, see Eq. 2.2, is further divided by a factor of 1/2 to account for the Dirac nature of the dark matter.

As far as the complementary is concerned, let us start with indirect detection. As already anticipated above, leptophilic dark matter features as final states charged leptons, which produce gamma rays. One of the most constraining and robust limits for a continuum gamma-ray spectrum is provided by the Fermi-LAT bounds from dwarf spheroidal galaxies (dSphs) (Albert 2017). In order to calculate the limits at 90% CL for the dSph Fermi-LAT constraint we use the likelihood method implemented within MadDM for determining the exclusion limits given the specific model realisation. We adopt the J-factors for ultrafaint dSphs (which were also used in Ambrogi et al. (2019)) from Ando et al. (2020), where more realistic assumptions for satellite formation are made to compute the J-factors from stellar kinematic for ultrafaint dSphs. This has the impact of weakening the Fermi-LAT bounds because ultrafaint dSphs contribute significantly to the exclusion limits. This updated J-factors modify the exclusion limits by roughly a factor of $\sim 4$ for $m_\chi \gtrsim 100$ GeV.

The exclusion limits for the case of annihilation into two body SM particles are based on energy spectra from PPPC4DM (Cirelli et al. 2011) including electroweak corrections implemented as in Ciafaloni et al. (2011). These are the same that are used for the KM3NeT analysis, see Sec. 2.7.1. For deriving the neutrino box spectra, we use the analytical formula provided in El Aisati et al. (2017) and the spectra with 4 leptons in the final state from PPPC4DM, in the case of Fermi-LAT bounds we generate the energy spectra with Pythia 8 (Sjöstrand et al. 2015), as implemented within MadDM. However we do not have the handling on the electroweak corrections for the 4 neutrino final state because those are not included in the Pythia 8 version released with MadDM. For dark matter masses well above the TeV scale, electroweak corrections are relevant and change the energy spectra especially of charged leptons and neutrinos. More importantly neutrinos emit electroweak radiation producing hence a secondary flux of gamma rays which can be constrained by gamma ray observations. Our bounds include the contribution of the gamma-ray flux from neutrinos in the Fermi-LAT dSph exclusion limits, similarly to Queiroz et al. (2016), in the case of two neutrino final state. Figure 2.13 illustrates that the recasted exclusion limits from gamma rays induced by neutrino final states are subdominant with respect to the gamma-ray exclusion limits coming from charged leptons, when those are present, for most of the relevant dark matter mass range. Intriguingly they overtake charged lepton exclusion limits above 5 TeV masses. This originates from the interplay of two
factors:

- The energy spectrum of gamma rays induced by electroweak corrected neutrino final states populates with more events the small gamma-ray energy ($E_\gamma$) range; this increases the sensitivity of Fermi-LAT measurements when the dark matter is heavy.

- The gamma-ray energy spectra from charged leptons take into account only the prompt gamma-ray contribution, which peaks towards large $E_\gamma/m_{DM}$. Since the sensitive energy window of Fermi-LAT is between 300 MeV up to 300 GeV, only the lower part of the energy spectra contribute in the case of heavy dark matter. This low energy part may receive additional contribution by the inclusion of additional secondary gamma rays, produced for instance by Inverse Compton scattering (ICS) processes, see e.g. this review Blumenthal & Gould (1970). It is however not clear how ICS would affect Fermi-LAT bounds for heavy dark matter, as there have not been thorough studies of ICS in dSphs, while radio emission and X-ray emission have been more deeply investigated, see e.g. Jeltema & Profumo 2008; Natarajan et al. 2015; Kar et al. 2020). Furthermore, the secondary gamma-ray flux relies on additional astrophysical assumptions for the modelling of the interstellar medium, hence the derived upper limits are subject to large uncertainties, similarly to the case of our galactic halo (Buch et al. 2015).

Regardless of these interesting details, we see that above dark matter masses of $\sim 500$ GeV, forecasted limits for KM3NeT show substantial gains over the Fermi-LAT limits.

The models we consider are leptophilic by constructions and naively, one would assume that they avoid all direct dark detection bounds since there is no tree level vertex which couples the quarks or gluons directly to the dark matter particle. However, renormalization effects (RGEs) generate effective couplings to the nuclei which lead to constraints from hadronic processes as shown in D’Eramo et al. (2016, 2017). To compute the effect of RGEs for the $Z'$ model we use RunDM\(^3\), while for the $t$-channel case we evaluate directly the loop diagrams (Cerdeno et al. 2019). The details on the specific contributions to the elastic scattering cross section is provided in the pertinent model sections. All models generate spin-independent couplings, hence we consider the effect of RGEs relating to the XENON1T experimental results (Aprile et al. 2018), recasted using the RAPIDD tool (Cerdeno et al. 2018). We additionally discuss the dependence of the XENON1T bound on astrophysical parameters such as the local dark matter density. We consider as reference value $\rho_\odot = 0.4$ GeV/cm\(^3\) (Bozorgnia et al. 2016), but exemplify ones the impact of this choice by considering the whole range of allowed values, $\rho_\odot = (0.2-0.4)$ GeV/cm\(^3\); see Ibarra et al. (2018) and

\(^3\)RunDM is available here https://github.com/bradkav/runDM (D’Eramo et al. 2016).
There are several constraints from collider experiments that may be relevant for our study. First it should be noted that we are interested in the electroweak production of the new mediator and/or dark matter particles, as the couplings to quarks are negligible by construction. The $t$-channel model can be searched for with pair-production of the charged $\varphi$, which consequently decays into two charged leptons and the dark matter ($pp \rightarrow \varphi^+\varphi^- \rightarrow \chi l^+l^-$, with $l = e, \mu$). This resembles to the supersymmetric search for slepton production in the simplified model framework (Aad et al. 2020b). Nevertheless, this search can constrain the mediator masses up to roughly 300 GeV, which is below the mass limits we consider in this study. As far as it concerns $s$-channel models with vector mediator, the most sensitive searches such as mono-X searches, di-leptons, di-quarks do not apply here, because they all assume a non-zero coupling with quarks, see for instance (Aad et al. 2019, 2020a, 2021a,b; Aaboud et al. 2018). The strongest constraint for vector mediator mass comes from LEP-II bounds for the process $e^+e^- \rightarrow f\bar{f}$ (where $f$ are the SM fermions) (Zyla et al. 2020) and states that $m_{Z'} \gtrsim 209 \text{GeV}$. We conclude that collider bounds are in general fairly limited for leptophilic dark matter models in the ball-park of detection of neutrino telescopes.

Very light vector mediators are allowed under the assumptions that the coupling references therein.
to leptons is tiny. Several constraints arise for mediators in the mass range in between MeV and GeV, most notably the search $Z \rightarrow 4\mu$ from BaBar (Lees et al. 2016) and CMS (Sirunyan et al. 2019). All the other constraints arise from neutrino physics, notably neutrino trident production (Altmannshofer et al. 2014a), neutrino-electron scattering in Borexino (Kaneta & Shimomura 2017) and neutrino cooling of white dwarfs (Bauer et al. 2020). In our analysis we will consider mediator masses down to 1 MeV, below the muon production threshold due to the two-body decay of the $Z'$. However our $Z'$ will couple very feebly with the SM particles by assumption, with couplings $\mathcal{O}(10^{-10} \rightarrow 10^{-7})$: this scenario is known as secluded dark matter (Pospelov et al. 2008b). Bounds from collider, neutrino and fixed target experiments can then be easily avoided in such configuration, however there are cosmological bounds which are of interest in the case of very light mediators and will be discussed in Sec. 2.7.4.

### 2.7.4 Model-dependent bounds

The simplest realisation of $t$-channel model consistent with $s$-wave annihilation features a singlet Dirac dark matter candidate and a scalar mediator. It is similar to dark matter $t$-channel models currently investigated at the LHC (Arina et al. 2020, 2021), with the difference that here the mediator is not a coloured particle as it couples to the SM leptons, see e.g. (Ibarra & Wild 2015). We find that this simple scalar model is severely constrained by direct detection experiments. Even in the most optimistic scenario of very large coupling strength, the parameter space that could be potentially surveyed by future generation of neutrino telescopes is already being strongly disfavoured by XENON1T. The inclusion of the other lepton flavours does not change the picture, as it will have the effect of strengthening more the XENON1T with respect to the improve in the KM3NeT sensitivity.

The most promising $s$-channel model features singlet Dirac dark matter candidate $\chi$ with a spin 1 mediator $Z'$. This model is very similar to the one used as benchmark at the LHC by the experimental collaborations (Aaboud et al. 2019; Sirunyan et al. 2018). The thermal annihilation cross-section for the $s$-channel process is maximised on resonance production, $2m_\chi \sim m_{Z'}$. The ultimate value on resonance is limited by the width of $Z'$ which is also set by the couplings $g_\chi$ and $g_l$. We find that the KM3NeT sensitivity for combined leptonic channels will be probing parameter spaces on the resonance which are currently beyond reach of Fermi-LAT. It is possible to construct a model that couples only to the $SU(2)_L$ lepton doublets of the SM. However with this model, it is arguable that we are on slightly less sturdy theoretical ground. Not only do we have a model that contains anomalies (Ellis et al. 2017), but more immediately issues with unitarity violation occur, see i.e. (Kahlhoefer et al. 2016).

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A well known, anomaly-free leptophilic scenario is the so-called $L_\mu - L_\tau$ gauge $U(1)$ model. This model assumes a specific gauge group under which the new particles are charged and gauged, which is defined as being the difference between muon- and tau-lepton numbers $L_\mu - L_\tau$. This model has been proposed in (He et al. 1991a,b; Foot et al. 1994; Baek et al. 2001; Ma et al. 2002; Heeck & Rodejohann 2011; Altmannshofer et al. 2014b) for solving the long standing flavour anomalies and has been studied i.e. in (Baek & Ko 2009; Biswas et al. 2017; Altmannshofer et al. 2016; Arcadi et al. 2018b) in connection with dark matter. The four free parameter of the model are:

$$\{m_\chi, m_{Z'}, g_\chi, g_{\mu-\tau}\}. \quad (2.16)$$

The expected sensitivity for the KM3NeT as well as the constraints from different experiments using this model are shown in Fig. 2.14 left, when $g_{\mu-\tau} = g_\chi = 1$ is satisfied. Besides having a well motivated theoretical model, we are in the same position as the simple $Z'$ models concerning the complementarity among direct, indirect dark matter bounds and the KM3NeT sensitivity.

The major contribution comes from the kinetic mixing $\varepsilon$, which will be generated at the loop level. The loop induced kinetic mixing is finite (Araki et al. 2017)

$$\varepsilon (q^2) = \frac{eg_{\mu-\tau}}{12\pi^2} \ln \frac{m_\mu^2}{m_\tau^2}, \quad (2.17)$$

and leads to sizeable values, for instance $\varepsilon \sim 10^{-2}$ for $g_{\mu-\tau} \approx 1$. Secondly, the same model can accommodate the favored region for flavor anomalies observed at LHCb (Aaij et al. 2014, 2017, 2019), red shaded region in the plot of Fig. 2.14. In order for this model to account for anomalies in $b \to s\mu^+\mu^-$ decays, it is necessary to assume that there is additional new physics. For our scope, a fourth generation of vector-like quarks coupling to the $Z'$ is a viable solution, as these new particles can be taken much heavier than the dark matter scale we are interested of, so that they can be safely integrated out without affecting our phenomenological predictions (Algueró et al. 2019; Altmannshofer et al. 2020; Di Luzio et al. 2019). For details about the favoured region derivation see i.e. (Altmannshofer et al. 2016; Altmannshofer & Yavin 2015; Altmannshofer et al. 2014b).

From Fig. 2.14 this gauged model has the benefit of being gauge invariant but does not seem to give KM3NeT a huge competitive edge. However, this model can easily accommodate a light $Z'$, which is exactly the same ball park of mediator masses employed to explain the $(g-2)_\mu$ anomaly (Bennett et al. 2002, 2004, 2006; Roberts 2010), see e.g. the recent (Amaral et al. 2020). We use the fact that, for $m_{Z'} < 2 m_\mu$, the branching ratio to neutrinos is 100%. This is favourable to neutrino telescopes, both those such as Super-Kamiokande (Abe et al. 2020), which are sensitive to light dark matter (Klop & Ando 2018; Asai et al. 2021), as well as those most sensitive to heavier dark matter, such as KM3NeT.
Figure 2.14: Left: The projected sensitivity of KM3NeT (green) together with current bounds from Fermi-LAT dSphs obtained with MadDM (gray) (Albert 2017) and XENON1T (light blue) (Aprile et al. 2018) obtained with RAPIDD, as labelled, in the \( \{m_\chi, m_{Z'}\} \)-plane for fixed equal couplings of \( g_{\mu-\tau} = g_\chi \). The black dotted lines are where \( \sigma_v = 2 \times 10^{-26} \text{ cm}^3/\text{s} \), i.e. the value for simple freeze-out. All exclusion limits and projection are provided at 90% CL. The red shaded regions illustrates the favored region (Altmannshofer et al. 2016) for explaining the flavour anomalies found at LHCb (Aaij et al. 2014, 2017, 2019).

Right: The projected sensitivity of KM3NeT (green) together with current upper bound from Planck (blue) (Bringmann et al. 2017; Slatyer 2016; Arkani-Hamed et al. 2009), as labelled, in the \( \{m_\chi, m_{Z'}\} \)-plane for fixed couplings of \( g_{\mu-\tau} \ll g_\chi = 1 \). The yellow region denotes the model parameter space favoured to alleviate the Hubble tension (Bernal et al. 2016; Escudero et al. 2019). The dotted black line represents the relic density line.

Of course, with a new light vector, relatively large couplings with SM particles are strongly constrained by colliders and precision experiments. It is, however, completely legitimate to take \( g_{\mu-\tau} \ll g_\chi \). This model comes under the category of secluded dark matter models (Pospelov et al. 2008b), and specifically features a very light mediator \( m_{Z'} \ll m_\chi \), large and perturbative \( g_\chi \) while negligible coupling to the SM sector, \( g_{\mu-\tau} \lesssim 10^{-4} \) at least. This last requirement is set to evade strong constraints on light fields coupling to SM leptons, but the meaning of this model is deeper than simply avoiding experimental bounds. For such coupling strength hierarchy, the dominant annihilation channel is \( \chi \bar{\chi} \rightarrow Z'Z' \) (see Fig. 2.12 centre), which implies that the dark matter can achieve the correct relic density independently of its coupling with the SM, because \( \sigma_v \) depends only on \( g_\chi^4 \). Since the \( Z' \) is not stable, it will eventually decay into four SM neutrinos, even though \( g_{\mu-\tau} \) is extremely tiny. Depending on the \( m_{Z'} \) value, annihilation into charged leptons, when kinematically allowed, takes place with equal
branching ratios and gives rise to a $4\mu$ or $4\tau$ final state. For simplicity we do not consider mixed final states in this study. Very light $Z'$ mediators are boosted in the very heavy dark matter annihilation reference frame. Subsequently, they decay into neutrinos producing characteristic box-shaped neutrino signals. While the box-shaped gamma-ray signals have already been explored in certain depth in the literature, see i.e. (Ibarra et al. 2012, 2013, 2015; Leane et al. 2017; Arina et al. 2017), box-shaped neutrino signals have only been poorly studied, see (El Aisati et al. 2017).

Let us now quantify how constrained the model parameter space is in the light of current bounds. In the secluded regime, high intensity experiments constrain $g_{\mu-\tau} \lesssim 10^{-4}$ for $m_{Z'} \lesssim 10$ GeV (Escudero et al. 2019), while Big Bang Nucleosynthesis (BBN) sets a lower bound on the coupling strength not to spoil its accurate predictions in terms of element abundances with the injection of energy. Indeed the $\chi\chi \to Z'Z'$ process is independent to $g_{\mu-\tau}$, however one cannot choose an arbitrarily small value as a sufficiently long lived $Z'$ will disrupt BBN. A conservative bound would be taking the lifetime sufficiently short such as

$$\tau_{Z'} = \sum_f \frac{12\pi m^2_{Z'}}{g^2_{\mu-\tau} \sqrt{m^2_{Z'} - 4m^2_f} \left(m^2_{Z'} - m^2_f\right)} \lesssim 1 \text{ s,}$$

(2.18)

where $m_f$ is the mass of the products of decay and $f$ runs over the fermionic decays kinematically allowed. This bound sets $g_{\mu-\tau} > 10^{-10}$ for $m_{Z'} = 1$ MeV, while being looser at larger dark matter masses. Notice that scenarios for the $(g-2)_\mu$ anomaly favour couplings of $g_{\mu-\tau} \sim 10^{-5}$. A more stringent bound comes from measurements of $\Delta N_{\text{eff}}$, the effective relativistic degree of freedom before recombination (Escudero et al. 2019; Aghanim et al. 2020), which sets a bound on the $Z'$ mass to be larger than 4 MeV roughly, by asking $\Delta N_{\text{eff}} \leq 4$. The constraints on a light $Z'$ are of course independent of dark matter, so we have to add direct dark matter detection limits as before. Now however, the smaller values of $m_{Z'}$ do not suppress the recoil rate so much, resulting in strong constraints on $g_{\mu-\tau}$, which are relevant for $m_\chi > 6$ GeV and set $g_{\mu-\tau} < 10^{-6}$ from XENON1T. We have checked that $g_{\mu-\tau} < 10^{-8}$ produces nuclear recoil event rates well below the sensitivity of future direct detection experiments. We see that in between the upper and lower bound there is still room to play safe and evade all constraints. What can not be avoided are indirect detection bounds, which come from Fermi-LAT and Planck (Aghanim et al. 2020). Indeed $\langle \sigma v \rangle$ is severely boosted by the small velocities in dSphs or at the recombination epoch, as a light mediator induces Sommerfeld enhancement, which we properly include as in (Hisano et al. 2005; Arkani-Hamed et al. 2009; Iengo 2009; Cassel 2010; Arina et al. 2010). Lastly, self-interaction constrains the size of the scattering process $\chi\chi \to \chi\chi$, see e.g. (Bringmann et al. 2017), impacting the region of small dark matter masses and very light mediators.

The results are shown in the right panel of Fig. 2.14. We see for $m_{Z'} > 2m_\mu$ the model parameter space is strongly disfavoured by current bound from Planck,
computed as in (Bringmann et al. 2017; Slatyer 2016; Arkani-Hamed et al. 2009). This bound supersedes Fermi-LAT dSph upper limit (not shown) because dSphs are warmer than the epoch of recombination, and this is reflected in a smaller Sommerfeld boost. However, neutrino telescopes can access the model parameter space below the kinematic threshold of the muon final state, being able to probe the model parameter space proving the correct relic density. The dip in the KM3NeT bound is due to the opening of the charged lepton final states, which increases $\langle \sigma v \rangle$. In the same ball park, $m_{Z'} \sim 10$ MeV can also contribute to the resolution of the Hubble tension (Aghanim et al. 2020; Riess et al. 2016, 2018, 2019) (yellow shaded band). More specifically, the light vector would contribute to increase $\Delta N_{\text{eff}}$ up to roughly $0.2 - 0.4$ (Bernal et al. 2016; Escudero et al. 2019), value that can reconcile the determination of $H_0$ from local measurements with the one from the cosmic microwave background. Self-interaction bounds are not shown to avoid cluttering, as they exclude a small portion of the lower left corner, which is already disfavoured by $\Delta N_{\text{eff}}$. Lastly, notice that we did not include electroweak radiation from the prompt neutrino final states. This would have the effect of generating a bound from the recombination epoch for dark matter above the TeV, where electroweak corrections are sizeable. All in all the region below the muon threshold is a sweet spot for revealing the best capabilities of KM3NeT, especially for dark matter below the TeV scale, but it remains to future work to determine whether electroweak corrections provide Planck with the means to constrain this region.

2.8 Conclusion

In this chapter, we have derived constraints on the lifetime and cross-section of dark matter with current and future neutrino telescopes. We have investigated the two-component interpretation of the high-energy neutrino flux observed by IceCube. The possibility of two different components contributing to the observed neutrino flux in addition to the atmospheric background has been proposed to solve the slight tension between IceCube HESE and TG data. In order to constrain the total number of neutrino potentially related to dark matter, we have studied the angular power spectrum of neutrino sky maps for different scenarios: the null hypothesis of atmospheric neutrino background and an astrophysical power-law component, and the signal hypothesis that includes a dark matter component. While the former is nearly isotropic above 60 TeV, the latter is expected to correlate with the galactic halo of the Milky Way. By means of Monte Carlo simulations and a $\chi^2$ analysis, we have provided the current constraints on dark matter properties (lifetime and cross-section as a function of DM mass above 60 TeV) deduced from 6-year IceCube HESE shower data. Moreover, we have reported the future sensitivity to a dark matter signal after 10 years of observations with IceCube and with next-generation neutrino telescopes as
KM3NeT and IceCube-Gen2. KM3NeT has been found to be more sensitive to a dark matter component for low dark matter masses, thanks to the better sensitivity to the galactic center at energies below the threshold of Earth absorption. Finally, this analysis has shown that both KM3NeT and IceCube-Gen2 will be able to firmly probe the current 7.5-year HESE best-fit of the dark matter component by exploiting angular information only. This result is of paramount importance since it highlights a feasible and solid way to distinguish a dark matter signal to neutrino fluxes produced by potentially hidden astrophysical sources.

Moreover, we extended the analysis to lower energies for future KM3NeT data with dark matter mass range of 200 GeV to 100 TeV. We have interpreted the projected sensitivities with respect to minimal extensions of the SM that include a Dirac dark matter candidate and a mediator. The most promising for neutrino telescopes couples dark matter to SM leptons only and we have investigated an anomaly free and gauge invariant scenario, the so-called $L_\mu - L_\tau$ model.

By presenting our projections in the context of multiple experimental searches, we demonstrate a high degree of complementarity. As always, gamma-ray telescopes and direct dark matter detection experiments play an important role, but neutrino telescopes will be able to probe new regions of parameter space. We stress that independent experimental probes are vital for comprehensive search for dark matter. Each experiment has its own set-up and sources of uncertainty. A diverse range of probes is necessary to reduce bias, minimizing the impact of individual uncertainties and clarifies the particle physics interpretation. Improvements both in the analysis methods and theoretical implications of upcoming neutrino telescopes will have a large impact on our understanding of dark matter physics. They will additionally provide guidelines on how KM3NeT-like telescopes will complement other dark matter searches in the next decade.
Abstract

Dark matter might be made of “warm” particles, such as sterile neutrinos in the keV mass range, which can decay into photons through mixing and are consequently detectable by X-ray telescopes. Axionlike particles (ALPs) are detectable by X-ray telescopes too when coupled to standard model particles and decay into photons in the keV range. Both particles could explain the unidentified 3.5-keV line and, interestingly, XENON1T observed an excess of electron recoil events most prominent at 2 – 3 keV. One explanation could be an ALPs origin, which is not yet excluded by X-ray constraints in an anomaly-free symmetry model in which the photon production is suppressed. We study the diffuse emission coming from the Galactic halo, and calculate the sensitivity of all-sky X-ray survey performed by eROSITA to identify a sterile neutrino or ALP dark matter. We estimate bounds on the mixing angle of the sterile neutrinos and coupling strength of the ALPs. After four years of data-taking by eROSITA, we expect to set stringent constraints, and in particular, we expect to firmly probe mixing angle $\sin^2(2\theta)$ up to nearly two orders magnitude below the best-fit value for explaining the unidentified 3.5-keV line. Moreover, with eROSITA, we will be able to probe the ALP parameter space of couplings to photons and electrons, and potentially confirm an ALP origin of the XENON1T excess.

This work is based on Dekker et al. (2021b)
3 Searches for sterile neutrinos and axionlike particles from the Galactic halo with eROSITA

3.1 Introduction

The non-observation of CDM with direct detection experiments motivates to search for other candidates besides CDM; for example, dark matter with much lower masses such as warm dark matter (WDM) with non-negligible thermal velocity at early times (Roszkowski et al. 2018; Silk et al. 2010). Sterile neutrinos are well motivated WDM candidates (Shi & Fuller 1999b; Abazajian et al. 2001; Dolgov & Hansen 2002; Canetti et al. 2013) as they can possibly simultaneously explain baryogenesis, neutrinos mass, and dark matter, with sterile neutrino as the dark matter candidate in the neutrino minimal standard model (Boyarsky et al. 2009). Through a mixing angle $\theta$ with active neutrinos, sterile neutrinos can decay into an active neutrino and a photon with photon energy $E_\gamma = m_{\nu_s}/2$, where $m_{\nu_s}$ is the sterile neutrino mass. The rate of decay depends on its mass and mixing angle, and is given by the following decay rate (Sicilian et al. 2020; Abazajian 2021),

$$\Gamma_{\nu_s}(m_{\nu_s}, \theta) = 1.38 \times 10^{-29} \text{s}^{-1} \left[ \frac{\sin^2(2\theta)}{10^{-7}} \right] \left( \frac{m_{\nu_s}}{1 \text{ keV}} \right)^5. \quad (3.1)$$

Sterile neutrinos in the keV mass range will produce X-ray photons, which can be observed by X-ray telescopes as a monochromatic line signal. Through a stacked X-ray spectrum analysis of 73 galaxy clusters, an emission line at $\sim 3.5$ keV was detected (Bulbul et al. 2014a), hinting towards experimental evidence for sterile neutrino decay. Many follow-up studies confirmed the line (Iakubovskyi et al. 2015; Franse et al. 2016; Cappelluti et al. 2018; Neronov et al. 2016), while other studies did not detect any line emission in dark matter dominated objects (Urban et al. 2015; Tamura et al. 2015; Riemer-Sørensen et al. 2015; Malyshev et al. 2014a; Anderson et al. 2015; Foster et al. 2021; Bhargava et al. 2020). It therefore remains relevant to search for a line emission from sterile neutrino decays.

Another interesting WDM candidate is the axionlike particle (ALP), which is a pseudo-Nambu-Goldstone boson that emerges when a continuous global symmetry is spontaneously broken (Arias et al. 2012; Takahashi et al. 2020; Irastorza & Redondo 2018; Chaubey et al. 2020). In contrary to the QCD axions, ALPs do not solve the CP problem, and can be light due to the broken symmetry. ALPs can couple to various standard model particles such as protons, electrons, and photons, and therefore can decay into two photons, producing a narrow X-ray line, possibly explaining the unidentified 3.5-keV line.

As another interesting possibility, ALP decay could explain the observed excess of electron recoil events over known backgrounds at the XENON1T experiment, where a best-fit mass value of $m_a = 2.3$ keV and coupling to electrons of $g_{ae} \sim 10^{-13}$ is found with a $3\sigma$ significance over the background (Aprile et al. 2020). The ALP coupling to standard model particles is already too tightly constrained by X-ray observations to explain this excess. Therefore, the photon coupling needs to be suppressed (Irastorza
3.1 Introduction

In an anomaly-free symmetry model, the ALP is coupled to leptons without any anomalous coupling to photons, and is dominated by the coupling to the least massive lepton – the electron (Nakayama et al. 2014; Pospelov et al. 2008a; Takahashi et al. 2020). In this model, photons are only induced through threshold corrections, and, although suppressed, the decay into two photons can be the leading decay mode for ALPs with masses less than twice the electron mass.

The ALP-electron coupling suggested by XENON1T is of the same order as the coupling suggested to explain the observed excess in cooling of various stellar objects like white dwarfs and red giants (Giannotti et al. 2017), known as the stellar cooling anomalies (Miller Bertolami et al. 2014; Ayala et al. 2014; Corsico et al. 2012a,b). The evolution of these objects are described by well-established cooling process, and indeed, the cooling anomaly based on white dwarf luminosity function analysis is found at $4\sigma$ (Giannotti et al. 2016), hinting towards a preferred region for the ALP parameter space. Following Takahashi et al. (2020), we consider a model in which ALPs can explain both the XENON1T excess and the stellar cooling anomaly.

Whether dark matter is made of sterile neutrinos or ALPs, they can be well probed with current generation and future X-ray telescopes. In this paper, we estimate the sensitivity of all-sky X-ray survey performed by eROSITA to observe a decaying sterile neutrino and axion-like particle signal. The hierarchical clustering of dark matter predicts that the Milky-Way galaxy is embedded in a halo of dark matter particles, with a higher density towards the Galactic center (Navarro et al. 1997). The largest contribution to the observable dark matter induced X-ray flux originates from the Galactic center, and we study the diffuse emission coming from the Galactic halo around its center. eROSITA has excellent angular and energy resolution, and will also observe the full sky over the course of four years with an average exposure of 2.5 ks (Merloni et al. 2012), making the survey a valuable probe for dark matter decay with a narrow X-ray line emission. By simulating the all-sky X-ray signal due to dark matter decay, we make a sensitivity projection for eROSITA to a sterile neutrino and ALP signal under a background-only hypothesis. We find that the eROSITA will enable us to probe much deeper regions of the parameter space for both the sterile neutrino and ALP dark matter.

The chapter is organised as follows. In section 3.2, we describe the main features of the all-sky X-ray maps. In section 3.3, we present our analysis methodology, followed by the results and discussions in section 3.4, and the conclusion in section 3.5.
3.2 All-sky X-ray map

Sterile neutrino signal from the Galactic halo

The X-ray photon flux produced through sterile neutrino decay inside the Galactic halo depends on the sterile neutrino decay rate $\Gamma_{\nu_s}$, sterile neutrino mass $m_{\nu_s}$, energy spectrum $dN_{\text{decay}}/dE$ per decay, and the dark matter density distribution through the so-called D-factor as discussed in Chapter 1.5.3. The X-ray photon intensity is given as follows,

$$\frac{d\Phi}{dE} = \frac{\Gamma_{\nu_s}}{4\pi m_{\nu_s}} \frac{dN_{\text{decay}}}{dE} D.$$  \hfill (3.2)

The flux $F$ per pixel is given by integrating $\Phi$ over the pixel solid angle $\Delta\Omega$. The energy spectrum per decay is a delta function:

$$\frac{dN_{\text{decay}}}{dE} = \delta \left( E - \frac{m_{\nu_s}}{2} \right).$$  \hfill (3.3)

The D-factor describes the dark matter density profile, $\rho$, of the Milky Way halo, integrated over the line of sight $s$ is given by

$$D = \int ds \rho(r(s,l,b)),$$  \hfill (3.4)

where the radial distance from the Galactic center is described as

$$r = \sqrt{s^2 + R^2 - 2sR \cos l \cos b},$$  \hfill (3.5)

with $(l,b)$ the Galactic coordinates, and $R = 8.5$ kpc the distance from the Sun to the Galactic center. We consider both the spherically-symmetric Navarro-Frenk-White (NFW) (Navarro et al. 1997) profile, as described in Chapter 1.5.3, and a cored profile (Read et al. 2016a). The cored profile is given by

$$\rho_c(r) = f(r) \rho_{\text{NFW}}(r) + \frac{1 - f^2(r)}{4\pi r^2 r_c} M_{\text{NFW}}(r),$$  \hfill (3.6)

where the function, $f(r) = \tanh(r/r_c)$, considers the shallowness of the dark matter core below the core radius $r_c$. $M_{\text{NFW}}(r)$ is the enclosed mass for the NFW density profile within $r$ that is given by

$$M_{\text{NFW}}(r) = M_{200} g_c \left[ \ln \left(1 + \frac{r}{r_s}\right) - \frac{r}{r_s} \left(1 + \frac{r}{r_s}\right)^{-1} \right],$$  \hfill (3.7)

where $M_{200} = 1.11 \times 10^{12} M_\odot$, $g_c = 1/\log(1 + c) - c/(1 + c)$, and $c = 12.2$ is the halo concentration parameter (Read et al. 2016a). In our analysis we consider only

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3.2 All-sky X-ray map

complete core formation, reducing the number of parameters needed to specify the dark matter core properties. Adopting the parameters from (Abazajian et al. 2020) for both NFW and cored profile, we set the core radius \( r_c \) of the Milky Way to 1 kpc and use a scale radius of \( r_s = 26 \) kpc. For the local dark matter density we take \( \rho_0 = 0.28 \) GeV cm\(^{-3} \), for which we find a density at the scale radius of \( \rho_s = 0.16 \) GeV cm\(^{-3} \).

Extragalactic sterile neutrino signal

Additionally, decaying sterile neutrino contributes to the diffuse extragalactic signal, emitting at different redshifts. The average X-ray photon intensity is given as follows,

\[
\frac{d\Phi_{eg}}{dE} = \frac{\Gamma_{\nu_s} \Omega_{DM} \rho_c}{4\pi m_{\nu_s}} \left( \frac{dz}{H(z)} \delta \left( E(1 + z) - \frac{m_{\nu_s}}{2} \right) \right),
\]

with \( H(z) = H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda} \) the Hubble parameter as a function of redshift \( z \), and with \( H_0 = 70 \) km s\(^{-1} \) Mpc\(^{-1} \), \( \Omega_m = 0.27 \), \( \Omega_\Lambda = 0.73 \), \( \Omega_{DM} = 0.22 \), and the critical density \( \rho_c = 5.2 \times 10^{-6} \) GeV cm\(^{-3} \).

Figure 3.1 shows the integrated flux for the extragalactic (green solid line) and Galactic component by adopting NFW (orange solid line) and cored (purple dotted line) profiles as a function of angle \( \Psi \) subtending from the Galactic center in the energy range of \([4.1 : 4.9]\) keV, with \( m_{\nu_s} = 9 \) keV and \( \Gamma_{\nu_s} = 10^{-28} \) s\(^{-1} \). The Galactic flux associated with the cored profile is only slightly smaller with respect to that with the NFW profile at angles close to the Galactic center, and nearly identical further away. Furthermore, the extragalactic flux is more than an order of magnitude smaller than the Galactic flux within the small energy bins that we adopt in this paper and including the extragalactic flux will thus not lead to any significant improvement.

Axionlike particle signal

ALPs can couple to several standard model particles. Here we consider the coupling to photons and electrons. In the case of a ALP-to-photon coupling, the decay into two photons produces a mono-energetic line at the energy of \( m_a/2 \), with a decay rate given by (Higaki et al. 2014a)

\[
\Gamma_{a\rightarrow\gamma\gamma} \simeq 5 \times 10^{-29} \left( \frac{m_a}{7 \text{ keV}} \right)^3 \left( \frac{f_a}{5 \times 10^{14} \text{ GeV}} \right)^{-2} \text{ s}^{-1},
\]

where \( m_a \) is the ALP mass and \( f_a \) is the decay constant. One can convert the decay constant to the photon coupling \( g_{a\gamma\gamma} \) through the following conversion

\[
f_a \equiv \frac{\alpha C_{a\gamma\gamma}}{2\pi g_{a\gamma\gamma}},
\]
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Figure 3.1: The integrated flux as a function of the angle from the Galactic center $\psi$ for the Galactic component with both NFW (orange solid line) and cored profiles (purple dotted line), and the extragalactic component (green solid line). Sterile neutrino mass of 9 keV and energy range between 4.1 and 4.9 keV are adopted.

with $C_{\alpha\gamma\gamma} = 8/3 - 1.92 \approx 0.75$ (Irastorza & Redondo 2018).

In order to explain the XENON1T excess by ALP, the ALP-photon coupling must be suppressed due to existing bounds (Irastorza & Redondo 2018). We therefore consider ALPs that couple mainly to electrons, and assume an anomaly-free symmetry, where photons are only induced through threshold corrections. In this model, the decay rate is given by (Nakayama et al. 2014)

$$\Gamma_{\alpha \rightarrow \gamma \gamma} \approx 3.5 \times 10^{-57} \text{ GeV} \left( \frac{m_\alpha}{2 \text{ keV}} \right)^7 \left( \frac{g_{ae}}{5 \times 10^{-14}} \right)^2,$$

(3.11)

with $g_{ae}$ the coupling between the ALP and electron. The energy spectrum for the ALP is described by a delta function, as in equation 3.3, where we replace $m_\nu_s$ by $m_\alpha$. We further multiply the delta function by a factor of two to take into account that two photons are produced from the ALP decay. This allows for a direct comparison with the sterile neutrino flux and allows us to use the obtained X-ray bounds on the mixing angle and to convert to those on the coupling strength $g_{\alpha \gamma \gamma}$ or $g_{ae}$. It is therefore only necessary to construct sky maps for the sterile neutrino case, and the
method for producing these maps is described in the following section.

### Sky maps

The sky maps are generated with HEALPix\(^1\) using the software package healpy (Gorski et al. 2005; Zonca et al. 2019), where we adopt its resolution parameter Nside = 64, which corresponds to a pixel size \(\Delta \Omega = 0.84 \text{ deg}^2\). For each set of parameters \((m_{\nu_s}, \Gamma_{\nu_s})\), and for each energy bin of width \(\Delta E = E_2 - E_1\), we obtain the expected number of X-ray photon counts from decaying sterile neutrinos coming from the galactic halo as well as extragalactic from a region on the sky \(\Delta \Omega\) at position \((l, b)\) by

\[
N(l, b) = T \int_{E_1}^{E_2} dE A_{\text{eff}}(E) \int dE' P(E, E') \frac{dF}{dE'},
\]

where \(T = 2.5\) ks is the exposure time, \(A_{\text{eff}}(E)\) is the effective area and \(P(E, E')\) takes into account the energy resolution of the detector. We apply the following normal distribution for the energy resolution,

\[
P(E, E') = \frac{1}{\sqrt{2\pi} \sigma_E} \exp \left[ -\frac{(E - E')^2}{2\sigma^2_E} \right],
\]

where \(\sigma_E\) is related to the full width at half maximum through FWHM = \(2/\sqrt{2\ln 2}\) with FWHM = 138 eV for eROSITA (Merloni et al. 2012). We consider in total 13 energy bins around \(m_{\nu_s}/2\) with bin size \(\sigma_E\) for each sterile neutrino mass, and range the mass between \(m_{\nu_s}[2 : 20]\) keV.

### Background events

We consider an overall diffuse cosmic X-ray background (CXB), which is energy dependent and especially dominant at lower keV energies. It is represented by a power-law with photon index \(\Gamma = 1.42 \pm 0.03\) and with a normalization at 1 keV of \(8.44 \pm 0.24\) photon cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\) sr\(^{-1}\) (Lumb et al. 2002). Moreover, we consider eROSITA’s detector background, which are high energy particles that show a flat spectral energy distribution with a normalization of \(3.5 \times 10^{-4}\) counts keV\(^{-1}\) s\(^{-1}\) arcmin\(^{-2}\) (Predehl et al. 2021). We distribute both background contributions isotropically over the sky and apply the same energy binning as mentioned above.

Besides the isotropic background contributions, X-ray bubbles are observed in the Milky Way, which are most prominent in the 0.6 – 1 keV energy band and drop below the detector’s background above \(\sim 2.3\) keV (Predehl et al. 2020). An average count rate is measured by eROSITA in the 0.6 – 1 keV energy band of 0.0038 photons s\(^{-1}\)

\(^1\)http://healpix.sf.net
3 Searches for sterile neutrinos and axionlike particles from the Galactic halo with eROSITA

arcmin$^{-2}$ and 0.0026 photons s$^{-1}$ arcmin$^{-2}$ in the northern and southern bubbles respectively. We adopt a thermal spectrum to model the X-ray bubbles with a temperature of 0.3 keV (Predehl et al. 2020), where we fix the normalization with the aforementioned count rates. For its morphology, we consider an uniform template of the Fermi bubbles, downloaded from https://fermi.gsfc.nasa.gov/ssc/data/access/.

Moreover, in order to exclude the extended emission from the Galactic plane, we remove all pixels with $|b| < 20^\circ$. Figure 3.2 illustrates a sky map with energy bin around $m_{\nu_s} = 9$ keV with $\Gamma_{\nu_s} = 10^{-28}$ s$^{-1}$, corresponding to $\sin^2(2\theta) \simeq 9.3 \times 10^{-11}$, and additionally the isotropic and anisotropic background components. We analyze the full sky map under the signal hypothesis consisting of a sterile neutrino signal and background components, and under the null hypothesis with background components only.

![Figure 3.2: X-ray sky map with sterile neutrino signal with $m_{\nu_s} = 9$ keV, $\Gamma_{\nu_s} = 10^{-28}$ s$^{-1}$, as well as background components with 2.5 ks of eROSITA exposure within one energy bin around 4.5 keV whose width is $\sigma_E$. Pixels at the Galactic plane are removed with $|b| < 20^\circ$.](image-url)

3.3 Analysis

We calculate the sensitivity to detect a sterile neutrino signal by performing a joint likelihood analysis on simulated data. We generate mock data sets assuming background only (the null hypothesis with $\Gamma = 0$), with Monte Carlo simulations following a Poisson distribution. This is performed for each pixel of our pixelized sky map in
the binned energy window under consideration. For each sterile neutrino mass, we generate 500 mock data sets \( n_i \), where \( i \) runs over the energy bins as well as spatial pixels. The likelihood to obtain \( n_i \) as a function of the decay rate for a specific sterile neutrino mass is given by the likelihood functions:

\[
\mathcal{L}(\Gamma) = \prod_i P[n_i|\mu_i(\Gamma)] = \prod_i \frac{\mu_i(\Gamma)^{n_i} e^{-\mu_i(\Gamma)}}{n_i!},
\]

(3.14)

where \( \mu_i(\Gamma) \) are the expected counts in each bin under the signal hypothesis with decaying dark matter and background component. The test statistic (TS) to determine the best-fit model under a maximum likelihood estimation is then defined as

\[
\text{TS} = -2 \ln \left( \frac{\mathcal{L}(\Gamma)}{\mathcal{L}_{\text{max}}} \right),
\]

(3.15)

where \( \mathcal{L}_{\text{max}} \) is the the maximum likelihood. We obtain upper limits on the decay rates at 95% confidence level (CL), which corresponds to a test statistic of \( \text{TS} = 2.71 \).

### 3.4 Results and discussion

We analyse the simulated sky maps under the null hypothesis, and report the sensitivity of eROSITA on the mixing angle as a function of the sterile neutrino mass. Figure 3.3 shows the result by applying the NFW profiles by removing the Galactic plane with \( |b| < 20^\circ \). The two bands show the 68% and 95% containment regions from the Monte Carlo runs, while the solid line represents the median. The upper grey area represents limits based on current X-ray observations (Horiuchi et al. 2014; Ng et al. 2015; Perez et al. 2017; Ng et al. 2019; Abazajian 2017; Caputo et al. 2020; Roach et al. 2020; Foster et al. 2021), while the lower grey area represents the theoretical lower limit for dark matter underproduction (Serpico & Raffelt 2005; Cherry & Horiuchi 2017). With eROSITA, we will nearly close the gap between current lower and upper bounds. Reference (Barinov et al. 2021) obtains similar estimates at lower sterile neutrino masses by analyzing the signal from the inner 60° region around the Galactic center with eROSITA, whereas our estimates are stronger at larger sterile neutrino masses due to the larger region of interest as well as the removal of the Galactic plane. Moreover, we indicate the best-fit of the unidentified 3.5 keV line by Bulbul et al. (2014a) as a black star, with mass \( m_{\nu_s} = 7.1 \) keV and mixing angle \( \sin^2(2\theta) = 7 \times 10^{-11} \). With an exposure time of \( T = 2.5 \) ks, eROSITA will be sensitive to the 3.5 keV line and can even constrain the mixing angles up to nearly two orders of magnitude lower than the best-fit at \( m_{\nu_s} = 7.1 \) keV.

We evaluate how sensitive these results are to some aspects in our analysis. The median of the Monte Carlo runs with a cored profile is illustrated as the orange dashed dotted line, and by comparing with the NFW profile, we find little dependence on
the density profiles. Indeed, figure 3.1 shows that the difference between the density profiles is most prominent at the inner regions, which we exclude with the $|b| < 20^\circ$ cut. Additionally, we test the impact of excluding the Galactic plane at different latitudes, as shown in Fig. 3.4, after removing the galactic latitudes $|b| < 10^\circ$ (dashed), $|b| < 20^\circ$ (dashed dotted) and $|b| < 30^\circ$ (solid line) for a NFW density profile. As expected, including a larger latitude $|b| < 10^\circ$, shows slightly stronger constraints with respect to $|b| < 30^\circ$, however only by a factor of $\sim 1.2$. The X-ray bubbles contribute to the lowest energies we consider. However, since the sky coverage of the Fermi bubbles template is only 7\% (before masking), we find that our limits weaken only by a factor 1.1 at most by including the X-ray bubbles.

![Figure 3.3](image)

**Figure 3.3:** Sensitivity to the mixing angle as a function of the sterile neutrino mass for the cored (dashed orange) and NFW (green) profiles. The green bands show the 68\% and 95\% containment regions of the sensitivities and the median (solid line) from the Monte Carlo runs with an NFW profile. The black star indicates the best-fit for the unidentified 3.5 keV line with mixing angle $\sin^2(2\Theta) \simeq (0.2 - 2) \times 10^{-10}$ (Bulbul et al. 2014a), the upper grey area current X-ray constraints (Horiuchi et al. 2014; Ng et al. 2015; Perez et al. 2017; Ng et al. 2019; Abazajian 2017; Caputo et al. 2020; Roach et al. 2020; Foster et al. 2021), while the lower grey area indicates the theoretical upper bound for dark matter underproduction (Serpico & Raffelt 2005; Cherry & Horiuchi 2017).

The bounds on the mixing angle can be converted to the ALP-photon coupling $g_{a\gamma\gamma}$ and ALP-electron coupling $g_{ae}$, and the sensitivity of eROSITA to the photon coupling is shown in Fig. 3.5. Again, the best-fit for the 3.5 keV line is indicated by a black star, and with future eROSITA observations, an ALP scenario can be probed
3.4 Results and discussion

Figure 3.4: Sensitivity to the mixing angle, adopting a NFW density profile. The pixels with the following Galactic latitudes are removed: $|b| < 10^\circ$ (dotted), $|b| < 20^\circ$ (dashed dotted) and $|b| < 30^\circ$ (solid).

as an explanation for the unidentified X-ray line. Even though recent work found no evidence for an unassociated X-ray line (Foster et al. 2021), in which the current X-ray limits are shown as the grey shaded area (see Horiuchi et al. 2014; Ng et al. 2015; Perez et al. 2017; Ng et al. 2019; Abazajian 2017; Caputo et al. 2020; Roach et al. 2020; Foster et al. 2021), eROSITA will be able to probe a region of the parameter space not yet excluded by current X-ray limits.

Furthermore, we consider an anomaly-free ALP model in order to explain the XENON1T excess, an excess that has been observed to be most prominent at ALP mass of $m_a = 2\,–\,3$ keV and electron coupling $g_{ae} \sim 10^{-13}$, and has the best fit at $m_a = 2.3$ keV (Aprile et al. 2020). We test if eROSITA will be able to confirm this, and we show its expected sensitivity in Fig. 3.6, where the two bands show as before the 68% and 95% containment bands from the Monte Carlo runs, while the solid line represents the median. We show the region that is excluded by current X-ray observations in grey, and with eROSITA we can indeed probe a parameter space not yet constrained (Horiuchi et al. 2014; Ng et al. 2015; Perez et al. 2017; Ng et al. 2019; Abazajian 2017; Caputo et al. 2020; Roach et al. 2020; Foster et al. 2021). The black solid line represents the XENON1T limits (note that they are however given at 90% CL) (Aprile et al. 2020). The XENON1T excess best-fit may not be reached by future eROSITA data, however, if the best-fit alters towards $m_a \sim 3.5$ keV, which
is still inside the XENON1T excess region of interest with energies between 1–7 keV, an ALP origin could be confirmed. Interestingly, the expected sensitivity of Athena taken from Neronov & Malyshev (2016) show comparable sensitivity.

Moreover, the stellar cooling anomaly can be explained by an ALP contribution. The preferred region for the white dwarf cooling anomaly is illustrated as the yellow shaded area, while the preferred values for the red giant branch in globular clusters is illustrated as the yellow dotted line (Takahashi et al. 2020; Miller Bertolami et al. 2014; Viaux et al. 2013), and the preferred regions are close to the XENON1T excess. Reference (Takahashi et al. 2020) points out that the stellar cooling argument and the XENON1T excess cross each other for ALP constituting only a fraction $r \approx 0.1$ of the total dark matter, since the XENON1T data scales as $1/\sqrt{r}$. The excess could possibly be explained by a combination of ALP and another background component like tritium, as suggested by (Aprile et al. 2020).

**Figure 3.5:** Current and future limits on the ALP photon coupling. The blue bands show the 68% and 95% containment regions of sensitivities from the Monte Carlo runs and the blue solid line the median. The grey shaded area is described in Figure 3.3, and the black star indicates the best-fit from the unidentified 3.5 keV line with $g_{\alpha\gamma\gamma} \simeq (0.6 - 2) \times 10^{-18}$ (Bulbul et al. 2014a).
3.5 Conclusion

We searched for a decaying sterile neutrino and axionlike-particle (ALP) signal from the Galactic halo with all-sky eROSITA survey after four years observations. We generate mock data sets with the diffuse cosmic X-ray background and eROSITA’s detector background, as well as expected sky maps with counts from decaying sterile neutrinos in the Galactic halo. By performing a likelihood analysis, we set stringent bounds on the mixing angle of sterile neutrinos. We also convert these bounds to the ALP-photon coupling ($g_{a\gamma\gamma}$) and ALP-electron coupling ($g_{ae}$). We consider a cored and cusped Navarro-Frenk-White density profiles and find only tiny dependence on the choice of the density profile.

We will be able to probe a value for the mixing angle of sterile neutrinos up to nearly two orders of magnitude below the best-fit value that could explain the
unidentified 3.5 keV line (Bulbul et al. 2014a) and one order of magnitude stronger than the existing upper limits claimed in the literature (Horiuchi et al. 2014; Ng et al. 2015; Perez et al. 2017; Ng et al. 2019; Abazajian 2017; Caputo et al. 2020; Roach et al. 2020; Foster et al. 2021). In an accompanying paper (Ando et al. 2021), a similar analysis is performed discussing the eROSITA sensitivity to sterile neutrino decay based on analyzing Milky-Way satellite galaxies.

We will also be able to probe a large parameter space for the ALP couplings to photons and electrons that are not yet excluded by X-ray observations, to the same degree of improvement as in the case of sterile neutrinos. We investigate both a generic model for the ALP-to-photon coupling and a more specific anomaly-free symmetry that has been proposed to explain the XENON1T excess of electron recoil events (Aprile et al. 2020). Indeed, the XENON1T excess could possibly be explained by an ALP origin for an excess at $m_a \sim 3$ keV, which might be well tested with eROSITA.

We note that in estimating the sensitivity, all detector and astrophysical lines are neglected. It is understood that the sensitivity at these line energies would decrease significantly due to signal-background degeneracy. Near-future high-energy-resolution detectors, such as Athena and XRISM, may alleviate this by performing line diagnostics analysis based on different line shifts between signal and backgrounds (Speckhard et al. 2016; Powell et al. 2017; Zhong et al. 2020).
Abstract

Warm dark matter (WDM) can potentially explain small-scale observations that currently challenge the cold dark matter (CDM) model, as warm particles suppress structure formation due to free-streaming effects. Observing small-scale matter distribution provides a valuable way to distinguish between CDM and WDM. In this chapter, we use observations from the Dark Energy Survey and PanSTARRS1, which observe 270 Milky-Way satellites after completeness corrections. We test WDM models by comparing the number of satellites in the Milky Way with predictions derived from the Semi-Analytical SubHalo Inference ModelIng (SASHIMI) code, which we develop based on the extended Press-Schechter formalism and subhalos’ tidal evolution prescription. We robustly rule out WDM with masses lighter than 4.4 keV at 95% confidence level for the Milky-Way halo mass of $10^{12} M_\odot$. The limits are a weak function of the (yet uncertain) Milky-Way halo mass, and vary as $m_{\text{WDM}} \gtrsim 3.6\text{--}5.1$ keV for $(0.6\text{--}2.0) \times 10^{12} M_\odot$. For the sterile neutrinos that form a subclass of WDM, we obtain the constraints of $m_{\nu_s} > 12$ keV for the Milky-Way halo mass of $10^{12} M_\odot$. These results based on SASHIMI do not rely on any assumptions of galaxy formation physics or are not limited by numerical resolution. The models, therefore, offer a robust and fast way to constrain the WDM models. By applying a satellite forming condition, however, we can rule out the WDM mass lighter than 9.0 keV for the Milky-Way halo mass of $10^{12} M_\odot$.

This work is based on Dekker et al. (2021a)
4 Warm Dark Matter Constraints Using Milky-Way Satellite Observations and Subhalo Evolution Modeling

4.1 Introduction

An excellent probe to test the WDM models are the satellite galaxies in the Milky Way, as the abundance of these systems are suppressed for WDM models. Satellite galaxies are formed through complex astrophysical processes within dark matter subhalos (Wechsler & Tinker 2018; Somerville & Davé 2015), which are smaller halos that accreted onto a larger host. Subhalo properties can be well estimated using cosmological N-body simulations (Lovell et al. 2014; Tormen et al. 1997; Gao et al. 2004). They are, however, limited by numerical resolution, motivating towards accurate analytical and semi-analytical models. Indeed, in order to test WDM models by studying Milky-Way satellite counts, previous studies have discussed semi-analytical models, based on the extended Press-Schechter (EPS) formalism (Schneider 2015; Cherry & Horiuchi 2017). The EPS formalism provides analytical expressions for the hierarchical assembly of dark matter halos, where halos are formed through gravitational collapse of a density fluctuation above a critical value (Press & Schechter 1974; Bond et al. 1991; Lacey & Cole 1993). Not all subhalos host satellites and Refs. (Newton et al. 2021; Nadler et al. 2021b; Kennedy et al. 2014; Escudero et al. 2018) adopt a galaxy formation model for the galaxy-halo connection, while Refs. (Schneider 2015; Cherry & Horiuchi 2017) adopt a threshold on the halo mass above which star formation is initiated. These are, however, model-dependent and the results are affected by the choice of model parameters.

In this chapter, we present a semi-analytical model based on the EPS, combined with semi-analytical relations that describe the halo and subhalo evolution. Subhalos lose mass through gravitational tidal stripping after they accrete onto their host, changing the internal structure as well as completely disrupting subhalos within certain radii (Jiang & van den Bosch 2016; van den Bosch et al. 2005; Giocoli et al. 2008). This has not been taken into account in any previous semi-analytical work with WDM models, while it has been described for the case of CDM in Hiroshima et al. (2018a). In this work, we build on the semi-analytical models of Hiroshima et al. (2018a) and extend it to the WDM cosmology by modifying the mass-loss rate, and adopting appropriate changes to the EPS formalism (Benson et al. 2012) and to the concentration-mass-redshift relation for WDM (Ludlow et al. 2016). Our models enable us to directly probe subhalo properties for any WDM models as well as any halo and subhalo masses, resulting in competent and solid constraints, for which we make extensive comparison pointing out differences among various approaches.

We calculate the number of satellite galaxies in the Milky Way for a range of WDM and sterile neutrino models and compare them with the observed number of satellite galaxies. For observational data, we use 270 estimated satellite galaxies observed by the Dark Energy Survey (DES) and PanSTARRS1 (PS1) after completeness correction (Drlica-Wagner et al. 2020), as well as a subset of 94 satellite galaxies that contain kinematics data, to obtain lower limits on the WDM and sterile neutrino
4.1 Introduction

To derive our canonical, conservative constraints, we assume that all the sub-halos host satellite galaxies. Implementing galaxy formation in subhalos above some certain thresholds (such as mass) will effectively reduce the number of satellites that the models predict and lead to stronger limits. Therefore, we also investigate different galaxy formation conditions.

As a result, we obtain very stringent and model-independent constraints on the WDM masses of $> 3.6 - 5.1$ keV at 95% confidence level (CL), estimated for a range of Milky-Way halo masses $M_{200} = (0.6 - 2.0) \times 10^{12} M_\odot$ (Fig. 4.1), where $M_{200}$ is defined as the enclosed mass within the radii in which the mean density is 200 times the critical density. We also exclude the sterile neutrino dark matter with masses lighter than 12 keV for a Milky-Way halo mass of $10^{12} M_\odot$ (Fig. 4.2). By assuming that only halos with masses heavier than $10^8 M_\odot$ form galaxies in them, we obtain even more stringent (model-dependent) limits on the WDM masses of $> 9.0$ keV for Milky-Way halo mass $10^{12} M_\odot$.

Figure 4.1: Excluded regions at 95% CL of the WDM mass as a function of the Milky-Way mass considering the canonical constraints (red) as well as by adopting the satellite forming condition with $m_a > 10^8 M_\odot$ (yellow). Moreover, the conservative constraints considering satellites with kinematics data of $V_{\text{max}} > 4$ km/s are also shown (purple). The black markers represent limits from the literature (Sec. 4.5).
Figure 4.2: Excluded regions at 95% CL of the mixing angle $\sin^2(2\theta)$ as a function of sterile neutrino mass $m_{\nu_s}$ for the Milky-Way mass of $M_{200} = 10^{12} M_\odot$. The grey hatched area represents upper limits from the current X-ray constraints (Horiuchi et al. 2014; Ng et al. 2015; Perez et al. 2017; Ng et al. 2019; Abazajian 2017; Caputo et al. 2020; Roach et al. 2020; Foster et al. 2021) and the black star the best-fit of the unidentified 3.5 keV line with mixing angle, $\sin^2(2\theta) \simeq (0.2–2) \times 10^{-10}$ (Bulbul et al. 2014a; Boyarsky et al. 2014b).

4.2 Subhalo Models

4.2.1 Subhalo properties

In order to estimate the number of satellites in the Milky-Way halo, we need models that describe the formation and evolution of both halos and subhalos. The Milky-Way subhalos are characterized with the mass $m$, parameters $r_s$ and $\rho_s$ of the Navarro-Frenk-White (NFW) profile (Navarro et al. 1997), and the truncation radius $r_t$ beyond which the density quickly approaches to zero (Springel et al. 2008). All these quantities are at the current redshift $z = 0$, after the tidal evolution of the subhalos. In addition, some subhalos may get completely disrupted when the tidal effect strips substantial amount of masses in the outer radii such that $r_t < 0.77 r_s$ (Hayashi et al. 2003) (but see also van den Bosch et al. (2018)). It is therefore important to model the subhalo evolution, and relate the present quantities with those at accretion before experiencing tidal effects.
At the epoch of accretion when a halo becomes a subhalo, its density structure is completely characterized by three parameters: accretion redshift $z_a$, virial mass $m_a$, and the concentration parameter $c_a$. In our models, we obtain all the $z = 0$ subhalo quantities ($m$, $r_s$, $\rho_s$, and $r_t$) as a function of these three parameters as we describe below. Then the subhalo mass function, for example, can be computed as

$$
\frac{dN_{sh}}{dm} = \int dm_a \int dz_a \frac{d^2N_a}{dm_a dz_a} \times \int dc_a P(c_a|m_a,z_a) \delta_D(m - m(m_a,z_a,c_a)) \times \Theta(r_t(m_a,z_a,c_a) - 0.77r_s(m_a,z_a,c_a)),
$$

where $\delta_D$ is the Dirac delta function and $\Theta$ is the Heaviside step function. We can express distributions of any subhalo quantities (e.g., $r_s$, $\rho_s$, or the maximum circular velocity $V_{\text{max}}$) by using the same equation and by replacing the argument of the delta function accordingly. The number of subhalos $N_a$ accreted with mass $m_a$ at the redshift $z_a$ is encoded in $d^2N_a/(dm_a dz_a)$, which is described with the EPS formalism as discussed in the SM. For the distribution of the concentration parameter $c_a$, we adopt the log-normal function for the mean value $\bar{c}_a(m_a,z_a)$ obtained in Ludlow et al. (2016), and with standard deviation of $\sigma_{\log c} = 0.13$ (Ishiyama et al. 2013). To perform the integral, we uniformly sample the subhalo masses between $m_a = 10^5 M_\odot$ and $0.1 M_\odot$ using 500 logarithmic steps, and redshift between $z_a = 7$ and 0.1 with steps of $dz = 0.1$. Even though our models allow for finer resolutions, the adopted resolution reduces the computational time without affecting the results.

### 4.2.2 Matter power spectrum and critical overdensity

WDM suppresses gravitational clustering and erases cosmological perturbations at scales below the WDM free-streaming length, resulting in a cutoff in the power spectrum. The cut-off due to free-streaming effect of thermal WDM, can be described by a transfer function, $T^2(k)$, which gives the ratio in power spectra between a WDM and CDM universe as follows (Viel et al. 2005, 2012),

$$
T^2(k) \equiv \frac{P_{\text{WDM}}(k)}{P_{\text{CDM}}(k)} = (1 + (\alpha k)^{2.24})^{-5/1.12},
$$

$$
\alpha = 0.049 \left( \frac{1 \text{ keV}}{m_{\text{WDM}}} \right)^{1.11} \left( \frac{\Omega_{\text{WDM}}}{0.25} \right)^{0.11} \left( \frac{h}{0.7} \right)^{1.22},
$$

where $m_{\text{WDM}}$ is the WDM mass, and $P_{\text{CDM}}(k)$ the linear power spectrum for CDM which we obtain from the 7-year data WMAP observations (Komatsu et al. 2011) with corresponding cosmological parameters, $\Omega_{\text{WDM}} = 0.27$ and $h \equiv H_0/(100 \text{ km s}^{-1}) = 0.7$.

The variance of the power spectrum, $S$, is found by smoothing over a mass scale using a filter function. We adopt a “sharp-$k$” filter, which has been found to be
well suited for truncated power spectra (Benson et al. 2012; Lovell et al. 2016). The mass $M$ associated to the filter scale $R$ is, however, less well defined, and must be calibrated using simulations through a free parameter $c$, with $M = 4\pi \bar{\rho}(cR)^3/3$ and $\bar{\rho}$ the average matter density of the Universe. We adopt $c = 2.5$ (Schneider 2015).

While WDM particles are assumed to be produced thermally, sterile neutrinos are non-thermal at production and the power spectrum depends on their production mechanism. We adopt the Shi-Fuller (Shi & Fuller 1999a) mechanism in which a net lepton asymmetry value in the primordial plasma modifies the interactions between the plasma and active neutrino species, resulting in sterile neutrinos that are WDM particles as opposed to CDM production mechanisms (Petraki & Kusenko 2008; Kusenko 2006; Merle et al. 2014; Lello & Boyanovsky 2015; Patwardhan et al. 2015). We consider a wide range of lepton asymmetry values for each parameter set $(m_{\nu_s}, \sin^2(2\theta))$ in order to obtain the correct dark matter abundance. We use the public code sterile-dm to obtain phase-space distributions of $\nu_s$ and $\bar{\nu}_s$ (Venumadhav et al. 2016), and obtain the matter power spectrum using the Boltzmann code CLASS (Lesgourgues 2011).

Dark matter halos collapse above a critical threshold $\delta_c$, which is independent of the mass scale in the CDM case, while it does depend on the mass scale for the WDM case. Considering that halo formation is suppressed at small scale, collapse becomes more difficult below a characteristic mass scale. We consider the critical overdensity as a function of both the redshift and mass $\delta_c(M,z)$ (Benson et al. 2012). It can be described by fitting functions based on one-dimensional hydrodynamical simulations by Barkana et al. (2001), which studied the collapse thresholds for WDM by modelling the collapse delay due to pressure. We adopt their fitting functions given as

$$\delta_{c,WDM}(M,z) = \delta_{c,CDM}(z) \left[ h(x) \frac{0.04}{\exp(2.3x)} + (1 - h(x)) \exp \left( \frac{0.31687}{\exp(0.809x)} \right) \right], \quad (4.3)$$

where $x = \log(M/M_J)$ and $M_J$ the effective Jeans mass of the WDM defined as,

$$M_J = 3.06 \times 10^8 M_\odot \left( \frac{1 + z_{eq}}{3000} \right)^{1.5} \left( \frac{\Omega_m h^2}{0.15} \right)^{1/2} \left( \frac{g_X}{1.5} \right)^{-1} \left( \frac{m_{WDM}}{1.0 \text{keV}} \right)^{-4}, \quad (4.4)$$

with $z_{eq} = 3600(\Omega_m h_0^2/0.15) - 1$ the redshift at matter-radiation equality, $g_X = 1.5$ the effective number of degrees of freedom, $m_{WDM}$ the thermal WDM mass, and

$$h(x) = (1 + \exp[(x + 2.4)/0.1])^{-1}. \quad (4.5)$$

Sterile neutrinos are not thermal particles, and the sterile neutrino mass needs to be converted to its corresponding thermal relic mass in order to obtain the critical overdensity. We convert the mass through the half-mode wavenumber $k_{hm}$, which is the wavenumber at which the transfer function is given by $T^2(k_{hm}) = P_{\nu_s}/P_{CDM} = 0.5$. The half-mode wavenumber for thermal WDM is given by $k_{hm} = 
\( \frac{1}{\alpha} \left( 2^{1.12/5} - 1 \right)^{1/2.24} \) (Bose et al. 2015), where \( \alpha \) is a function of WDM mass as given by Eq. 4.2, and can thus be compared in order to obtain the conversion.

### 4.2.3 Subhalo evolution

After subhalos accrete onto their host halo, they lose mass under the gravitational tidal force exerted by the host halo. Tidal stripping has not been included in many previous analytical work (Schneider 2015; Benson et al. 2012; Menci et al. 2012), while it impacts on subhalo properties (Hiroshima et al. 2018a; Bartels & Ando 2015). Following Refs. (Jiang & van den Bosch 2016; Hiroshima et al. 2018a), the average mass-loss rate of dark matter subhalos is given as follows,

\[
\dot{m}(z) = -A \frac{m(z)}{\tau_{\text{dyn}}(z)} \left[ \frac{m(z)}{M(z)} \right]^{\zeta},
\]

where \( m(z) \) is the subhalo mass, \( M(z) \) is the host halo mass, and \( \tau_{\text{dyn}}(z) \) is the dynamical timescale. Through Monte Carlo modeling, we find \( A \) and \( \zeta \) as a function of both \( M(z) \) and \( z \) in a WDM universe; see App. 4.7.3 for more details. This simple modeling is proven to yield results that are consistent with those of numerical N-body simulations in the CDM case (Jiang & van den Bosch 2016; Hiroshima et al. 2018a). We solve this differential equation to obtain the subhalo mass at \( z = 0 \), which is uniquely determined given the initial condition \( m = m_a \) at \( z = z_a \).

The parameters of the NFW density profile, \( r_s \) and \( \rho_s \), as well as the truncation radius \( r_t \) also evolve as the mass loss proceeds. Reference (Peñarrubia et al. 2010) discusses the evolution of internal structure of subhalos by relating the maximum circular velocity \( V_{\text{max}} \) and corresponding radius \( r_{\text{max}} \) at accretion redshift \( z_a \) and at any later redshift (see App. 4.7.4 for details). We use those relations to calculate \( \rho_s \) and \( r_s \), and \( r_t \) at \( z = 0 \), all as a function of \( m_a, z_a \), and \( c_a \), in order to evaluate the subhalo number with Eq. (4.1).

### 4.3 Warm dark matter constraints

We obtain the expected number of subhalos in the Milky-Way by integrating Eq. (4.1). The number of subhalos depends on the Milky-Way mass, as a host with smaller mass will yield a smaller number of subhalos accreted onto it. The Milky-Way mass is uncertain and various work find values that are within the range of \( M_{200} = (0.6-2.0) \times 10^{12} M_\odot \) based on the latest Gaia data (Karukes et al. 2020; Posti & Helmi 2019; Eadie & Jurić 2019; Fritz et al. 2018). We consider this range of the Milky-Way mass to theoretically estimate the number of satellites.

Observationally, Drlica-Wagner et al. (2020) reports on ultrafaint Milky-Way satellite galaxies with the DES and PS1. They correct for the detectability of these satellites by fitting the luminosity function obtained from simulations of satellite galaxies.
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to the DES and PS1 satellite populations. After performing this completeness correction, 270 satellite galaxies are estimated to exist within 300 kpc from the Milky-Way center and for absolute V-band magnitude of $M_V < 0$.

The probability of obtaining the observed number of satellites $N$, for given number of satellites obtained from our models $\mu$ for each WDM parameter, is determined by the Poisson probability, $P(N|\mu) = \mu^N \exp(-\mu)/N!$. We rule out WDM models that predict too few satellite galaxies with respect to the observed number of satellites $N_{\text{obs}}$ at 95% CL as $P(> N_{\text{obs}}|\mu) = \sum_{N=N_{\text{obs}}}^{\infty} P(N|\mu) < 0.05$. The probability can also be described by a negative binomial distribution (Boylan-Kolchin et al. 2010), however we find that it has no significant impact on the results of this work. Moreover, there might be non-Poisson effects due to for instance spatial correlations with the Magellanic clouds (Newton et al. 2018a; Sales et al. 2011, 2007). These effects are expected to be minor and are not taken into account in this work.

For our canonical constraints, we assume that all subhalos host a satellite galaxy. This is, however, unlikely the case, and we could apply some satellite forming conditions. Since imposing galaxy formation will reduce the number of satellites, which goes along the same direction as the effect of the WDM free-streaming, doing so will strengthen constraints on the WDM masses. Therefore, with our canonical modeling, we obtain weaker, yet robust constraints on WDM.

In Fig. 4.1, we show the lower limits on the WDM masses at 95% as a function of the Milky-Way mass. In particular, the limits are stronger by a factor of 1.4 considering $M_{200} = 0.6 \times 10^{12} M_\odot$ with respect to the case of largest possible mass of $M_{200} = 2 \times 10^{12} M_\odot$. We find that we can rule out the WDM models with $m_{\text{WDM}} < 3.6 - 5.1$ keV at 95% CL for the possible range of the Milky-Way mass.

Next, we impose galaxy formation condition in our models. We adopt a model in which star formation is initiated through atomic hydrogen cooling, for which gas needs to cool down sufficiently to $\sim 10^4$ K. This is inefficient below halo mass (at accretion when it peaks) of $m_a \simeq 10^8 M_\odot$ (Sawala et al. 2015; Schneider 2015; Brooks & Zolotov 2014), which we apply as a minimum mass above which we assume that all subhalos form a satellite in them. We also show the constraints in this case in Fig. 4.1 and rule out WDM mass of 9.0 keV for a Milky-Way halo mass of $10^{12} M_\odot$. Moreover, for Milky-Way halo mass smaller than $0.9 \times 10^{12} M_\odot$, all WDM mass is excluded at 95% CL, and an accurate measurement of the Milky-Way halo mass could possibly become even inconsistent with both thermal WDM models and CDM.

The stellar kinematics data of the Milky-Way satellites are a powerful observable that also needs to be considered. Given that one of the observed satellites with the smallest velocity dispersion is Leo V with $\sigma = 2.3$ km s$^{-1}$, we opt to map this line-of-sight velocity dispersion to the halo circular velocity as $V_{\text{circ}} = \sqrt{3}\sigma = 4$ km s$^{-1}$ (Simon 2019), and use this estimate as the threshold of maximum circular velocity. Above this threshold $V_{\text{max}}$, there are 94 satellite galaxies in total; 82 estimated satellites based on the luminosity function after completeness correction, and 12 satellites
that were not included in the estimate of the luminosity function. Higher values of $V_{\text{max}}$ further reduce the number of luminous satellites. As shown in Fig. 4.1, we rule out $m_{\text{WDM}} < 2.2 - 3.5$ keV for the Milky-Way mass range of $(0.6 - 2.0) \times 10^{12}$ $M_\odot$.

### 4.4 Sterile neutrino constraints

We consider a wide range of sterile neutrino masses and mixing angles, and fix the lepton asymmetry values for each parameter set such that the correct relic density of dark matter is obtained, by adopting sterile neutrino production through to the Shi-Fuller mechanism. We estimate the number of satellites in the Milky Way with a best-fit Milky-Way mass of $M_{200} = 10^{12} M_\odot$ (Cautun et al. 2020), and note that our limits depend on the Milky-Way mass as shown in Fig. 4.1. The results are shown in Fig. 4.2, where the red area represents the excluded region at 95% CL considering 270 satellites. The lower grey area is excluded, as this parameter space corresponds to the maximum allowed lepton asymmetry, which is bounded by the Big-Bang nucleosynthesis to $L_6 \leq 2500$ (Serpico & Raffelt 2005; Boyarsky et al. 2009). The top grey area is excluded as the mixing is too large, resulting in dark matter overproduction.

The shape of the constraints is related to the sterile neutrino production. Non-resonant production results in warmer sterile neutrino spectral energy distributions, and thus in larger free-streaming effects. Indeed, the upper limit in Fig. 4.2 have stronger constraints as a result of less small-scale structure. Furthermore, very large lepton asymmetry delays the sterile neutrino production and yields warmer thermal distributions due to the frequent scattering between neutrinos and the plasma, and, indeed, we find stronger constraints towards the lower limit with $L_6 \leq 2500$ (Venumadhav et al. 2016).

Sterile neutrinos can decay through mixing into an active neutrino and a photon with $E_\gamma = m_{\nu_s}/2$, which could be observed by X-ray telescopes. Strong limits on the mixing angle are set by previous studies based on the current X-ray data (Horiuchi et al. 2014; Ng et al. 2015; Perez et al. 2017; Ng et al. 2019; Abazajian 2017; Caputo et al. 2020; Roach et al. 2020; Foster et al. 2021; Cappelluti et al. 2018; Dessert et al. 2020; Jeltema & Profumo 2015; Tamura et al. 2015; Malyshev et al. 2014b; Aharonian et al. 2017; Sekiya et al. 2015; Boyarsky et al. 2019c; Figueroa-Feliciano et al. 2015; Hofmann & Wegg 2019; Neronov et al. 2016), as indicated by the hatched grey area in Fig. 4.2. The black star indicates the best-fit of the unidentified 3.5 keV line with best-fit values $m_{\nu_s} = 7.1$ keV and mixing angle $\sin^2(2\theta) = 7 \times 10^{-11}$ (Bulbul et al. 2014a; Boyarsky et al. 2014b). The parameter space of sterile neutrinos is constrained to a great degree considering both X-ray and satellite constraints. In particular, sterile neutrino mass of $m_{\nu_s} \lesssim 20$ keV is excluded, which can also be confirmed with future X-ray data with all-sky X-ray instrument eROSITA (Dekker et al. 2021b; Ando et al. 2014b).
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2021; Barinov et al. 2021).

4.5 Discussion

In Fig. 4.1, we compare our limits with results from the previous papers. Among them, Nadler et al. (2021b) (triangle) adopted an empirical model for the galaxy-halo connection and obtained stringent limits of $m_{\text{WDM}} > 6.5$ keV. This is the result of inferring the peak halo mass above which halos host galaxies as one of the free parameters. It is similar to our approach using the $m_a > 10^8 M_\odot$ galaxy-formation threshold, for which we obtain comparable constraints. The results of Schneider (2015) is shown as the plus symbol, where a semi-analytical method is presented based on the EPS formalism and calibrated to numerical simulations, adopting the satellite forming condition on the minimum subhalo mass of $m_a = 10^8 M_\odot / h$. We improve on their work as we include tidal stripping effects for the first time, which results in fewer surviving satellites, and consider a larger data set. This also applies to results on the sterile neutrino constraints from Cherry & Horiuchi (2017) which adopted the same semi-analytical model from Schneider (2015), and find a constraint on the sterile neutrino mass of $m_{\nu_s} \gtrsim 6.5$ keV, which corresponds to the WDM mass of $m_{\text{WDM}} \simeq 2.5$ keV, indicated as the circle in Fig. 4.1.

Moreover, the dashed line represents the results from Newton et al. (2021), which similarly estimates the number of satellites based on the EPS method and calibrated to N-body simulations. As a second analysis, Newton et al. (2021) incorporates galaxy formation processes by using the semi-analytical model for galaxy formation GALFORM. Marginalizing over the uncertainties in the Milky-Way halo mass they rule out $m_{\text{WDM}} < 3.99$ keV, while they rule out $m_{\text{WDM}} < 2.02$ keV without incorporating a galaxy formation model.

The dotted line represents the results of Kennedy et al. (2014), where they obtain the limits based on the EPS formalism combined with GALFORM. Galaxy formation models are more physically motivated, but the results depend on the choice of various parameters. Indeed, depending on the choice of the main parameter of reionization, Kennedy et al. (2014) finds constraints that vary between $m_{\text{WDM}} < 2.5$ keV and being all ruled out for the Milky-Way halo mass of $2 \times 10^{12} M_\odot$.

We also show the limits based on N-body simulations, such as Lovell et al. (2014) (star) and Polisensky & Ricotti (2011) (cross). These numerical simulations are, however, limited by the numerical resolution, and moreover, Lovell et al. (2014) probes a maximum dark matter mass of up to $m_{\text{WDM}} \leq 2.3$ keV, while Polisensky & Ricotti (2011) probes five dark matter masses between $m_{\text{WDM}} = 1$ keV and 5 keV. We test our model with respect to the results from N-body simulations of Lovell et al. (2014), as discussed in the following section. We believe that our models are more flexible because they are not limited by numerical resolutions, and also allow setting model-
In our canonical model, we adopt a minimum subhalo mass at accretion (peak mass) of \( m_a = 10^5 M_\odot \). In order to effectively set a satellite forming condition, we impose a threshold on the peak mass of \( m_a > 10^8 M_\odot \), as has been done in the previous work (Schneider 2015; Cherry & Horiuchi 2017). Note, however, that the threshold on the peak mass is model-dependent, and we therefore show in Fig. 4.3 the effect of adopting different thresholds on the peak mass. We find that for a Milky-Way halo mass of \( M_{200} = 10^{12} M_\odot \), the constraints can vary between 4.5 keV and completely excluded by adopting a threshold on the peak mass between \( 10^7 M_\odot \) and \( 10^8 M_\odot \).

**Figure 4.3:** Lower limits at 95% CL on the WDM mass as a function of the Milky-Way mass considering different thresholds for galaxy formation on the peak subhalo mass \( m_a \).

In order to test our models with numerical simulations, we compare the suppression of the subhalo mass functions due to WDM with respect to CDM, defined as

\[
f(M, m_{WDM}) = \frac{(dN_{sh}/dM)_{WDM}}{(dN_{sh}/dM)_{CDM}},
\]

where \( M \) is the subhalo mass before mass loss. Based on high-resolution cosmological N-body simulations, Lovell et al. (2014) find a functional form for Eq. (4.7) by fitting the simulations with \( m_{WDM} = 2.3, 2.0, 1.6 \) and \( 1.5 \) keV. We compare the subhalo
mass function suppression in Fig. 4.4 for $m_{\text{WDM}} = 2.3$ keV with the Milky-Way mass of $M_{200} = 1.9 \times 10^{12} M_\odot$ (left), and 6.5 keV with $M_{200} = 1.4 \times 10^{12} M_\odot$ (right). We find a weaker suppression, but it differs at most by only a few tens of percent. The fitting function for subhalo mass before tidal stripping should, however, not be confused with the actual subhalo mass after it evolved due to tidal stripping, whereas there appears to be some level of confusion in the literature.

![Subhalo mass function suppression](image)

**Figure 4.4:** Subhalo mass function suppression of WDM with respect to CDM adopting $m_{\text{WDM}} = 2.3$ keV (left) and $m_{\text{WDM}} = 6.5$ keV (right). The subhalos mass $M$ is the virial mass before the tidal mass loss.

Next, we compare the cumulative maximum circular velocity and subhalo mass functions for subhalos after tidal stripping with the results from Lovell et al. (2014), as shown in Fig. 4.5. The dashed lines are the results from Lovell et al. (2014) and solid lines are our results. We find an underestimation with respect to the N-body simulation results; they differ by a factor of 1.6 at most for WDM, and a factor of 2.5 for CDM. Moreover, we also show two horizontal grey solid lines, that correspond to the number of observed satellites that we use in our analysis, $N_{\text{sat}} = 270$ and 94. The simulations by Lovell et al. (2014) are based on the Aquarius simulation for CDM (Springel et al. 2008). It was noted that the subhalo mass functions from Aquarius were found to be larger than the results of many other similar N-body simulations by a factor of a few. The cause of this discrepancy is not completely understood, but might be related to the halo-to-halo variance, as one cannot simulate very many Milky-Way-like halos with simulations like Aquarius that are tuned to have much greater numerical resolutions. In any case, if the WDM simulations were implemented based on other CDM runs, we expect that the degree of discrepancy that we see in Fig. 4.5 is much smaller. Thus, together with Fig. 4.4, we believe that our models based on SASHIMI predict subhalo quantities for both before and after the tidal mass loss in a WDM cosmology.

As far as we are aware, there is no convenient fitting function like the one proposed in Lovell et al. (2014) for the subhalo mass functions after the tidal mass loss. We
therefore encourage the community to use SASHIMI instead, whenever the subhalo properties after the tidal evolution are the quantities in question.

The number of satellites in the Milky-Way after completeness corrections has been found to be 124 in Newton et al. (2018b) by using a different method. Adopting 124 satellites instead of 270, however, we find that our canonical results become weaker by only $\sim 30\%$. Some of the observed satellites might be associated to the large Magellanic cloud, and they have been roughly estimated to contribute for at most 30\% to the observed satellites (Jethwa et al. 2016). This corresponds to 189 Milky-Way satellites, and we find $\sim 15\%$ weaker results.

Throughout this work, we do not incorporate baryonic effects, besides the effective prescription as a threshold mass $m_a > 10^8 M_{\odot}$, above which we assume no satellite forms in its host subhalo. In general, including baryonic physics would reduce the number of subhalos near the center of the main halo as subhalos are more strongly disrupted in the presence of baryons (Sawala et al. 2017), allowing for stronger constraints. Baryonic physics could be included in our model in future work by adding a central disk in the host halo, which has been shown to reproduce the subhalo depletion well due to the additional tidal field from the central galaxy (Garrison-Kimmel et al. 2017).

There are several other complementary approaches to test WDM models. By observing the spectrum of Lyman-$\alpha$ forests in high redshift quasars (McQuinn 2016), Iršič et al. (2017) sets a lower limit of $m_{\text{WDM}} > 5.3$ keV at 95\% CL. Strong gravitational lensing offers another approach to detect low-mass halos in the range of $10^6$–$10^{10} M_{\odot}$. References (Hsueh et al. 2019; Gilman et al. 2019) find lower limits of $m_{\text{WDM}} > 5.58$ keV and $m_{\text{WDM}} > 5.2$ keV at 95\% CL, respectively. Other independent approaches yield similar constraints (e.g., Banik et al. (2021); Shirasaki et al.
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(2021)).

4.6 Conclusion

The satellite number counts provide one of the most reliable and stringent constraints on long-debated WDM models, for which our semi-analytical approach that combines halo formation with tidal evolution enables predictions for a wide range of both WDM and Milky-Way halo masses. We make the numerical codes, Semi-Analytical Sub-Halo Inference Modelling (SASHIMI), publicly available for both CDM\(^1\) and WDM.\(^2\) SASHIMI provides a flexible and versatile platform for computing subhalo quantities and the constraints obtained with it are one of the best and most robust, being independent of physics of galaxy formation and free from numerical resolution and the Poisson noise. By comparing the latest satellite number counts obtained by the DES and PS1 surveys, we exclude the WDM masses for a wide range of Milky-Way halo mass, and find lower bounds of \(m_{\text{WDM}} > 4.4\) keV at 95% CL for Milky-Way halo mass of \(10^{12} \, M_\odot\), independent of galaxy formation physics. By adopting a galaxy-formation condition, we find that the limits significantly improve to \(m_{\text{WDM}} > 9.0\) keV. Moreover, we obtain limits on sterile neutrino masses of \(m_{\nu_s} > 12\) keV, and combined with current X-ray limits, \(m_{\nu_s} > 20\) keV. Our results thus show that there remain smaller rooms for warm particles such as thermal WDM and keV sterile neutrinos to be a dominant dark matter candidate.

4.7 Appendix

4.7.1 Mass Accretion History of the host halo

The mass function of WDM halos is suppressed with respect to CDM halos below the cut-off scale \(M_s \sim 10^8 \, M_\odot\) (Barkana et al. 2001). Meanwhile, the mean mass accretion history (MAH) above the cut-off scale shows almost no difference between WDM and CDM halos (Benson et al. 2012). This allows to adopt analytical expressions for the MAH that are derived for a CDM universe. In order to confirm this, we use the fraction of halo mass \((M_1, z_1)\) that is in progenitor halo mass at some later redshift \((M_2, z_2)\), where we use Model II for the fraction \(f(S_2, \delta_2 | S_1, \delta_1)\) as defined in Yang et al. (2011). By Monte Carlo method, we simulate 100 host halo masses with \(M_0 = 1.3 \times 10^{12} \, M_\odot\) for WDM mass \(m_{\text{WDM}} = 1.5\) keV between redshift \(z = 0\) and 10. We show the obtained MAH in Fig. 4.6, where the light blue lines show the individual MAH for each run, and the blue solid and dashed lines correspond

\(^1https://github.com/shinichiroando/sashimi-c\)

\(^2https://github.com/shinichiroando/sashimi-w\)
to the mean and the standard deviation respectively. We compare the results with the analytical expressions for the MAH from Correa et al. (2015a) obtained for a CDM universe, indicated by the red solid and dashed lines, representing the MAH and standard deviation $\sigma_{\log M_a} = 0.12 - 0.15 \log(M_a/M_0)$ respectively. They show similar behavior and we therefore adopt the analytical expressions from Correa et al. (2015a) for the MAH as follows,

$$M(z) = M_0(1 + z)^\alpha \exp(\beta z), \quad (4.8)$$

with parameters $\alpha$ and $\beta$

$$\beta = -f(M_0),$$
$$\alpha = \left[ 1.686(2/\pi)^{1/2} \frac{dD}{dz}\bigg|_{z=0} + 1 \right] f(M_0),$$
$$f(M_0) = [S(M_0/q) - S(M_0)]^{-1/2},$$
$$q = 4.137\tilde{z}_f^{-0.9476},$$
$$\tilde{z}_f = -0.0064(\log_{10} M_0)^2 + 0.0237(\log_{10} M_0) + 1.8827,$$

where $D(z)$ is the linear growth factor and $S(M) \equiv \sigma^2(M)$ the variance of the matter density smeared over scales corresponding to $M$ with some filter function. The MAH can be further generalized to obtain the mass $M(z)$ at redshift $z$, which had a mass of $M(z_i)$ at redshift $z_i$ (Correa et al. 2015b):

$$M(z) = M(z_i)(1 + z - z_i)^\alpha \exp(\beta(z - z_i)). \quad (4.9)$$

### 4.7.2 Mass Accretion History of the subhalo

With the expression for the MAH of the main branch, we can obtain the subhalo mass function accreted at a certain redshift onto the main branch, and we follow the model by Yang et al. (2011). The distribution of the masses $m_a$ and redshifts $z_a$ of subhalos that accreted onto the main branch of host halo that would evolve to $M_0$ at $z = 0$, is given by (Yang et al. 2011)

$$\frac{d^2N_a}{d\ln m_a dz_a} = \mathcal{F} \left( s_a, \delta_a | S_0, \delta_0; \overline{M}_a \right) \left| \frac{ds_a}{dm_a} \right| \left| \frac{d\overline{M}_a}{dz_a} \right|, \quad (4.10)$$

where $N_a$ are the number of subhalos of mass $m_a$ at accretion redshift $z_a$, $\overline{M}_a \equiv \overline{M}(z_a)$ is the mean mass of the main branch at accretion given by Eq. (4.8), $\mathcal{F} \left( s_a, \delta_a | S_0, \delta_0; \overline{M}_a \right)$ is the mass fraction in subhalos of mass $m_a$ at $z_a$ that accreted when the host was in the mass range $[\overline{M}_a - d\overline{M}_a, \overline{M}_a]$ as described hereafter. Furthermore, $s_a \equiv \sigma^2(m_a)$
and $S_0 \equiv \sigma^2(M_0)$ are the variances of the density fluctuation, and $\delta_a \equiv \delta_c(z_a)$ and $\delta_0 \equiv \delta_c(0)$, where $\delta_c$ is the threshold value of the gravitational collapse above which the overdense region is assumed to have collapsed to form a virialized halo. The variance and critical overdensity differ in the case of a WDM universe with respect to the standard CDM case in which the EPS formalism was described, and we incorporate adjustments as discussed in the section 4.2.2.

We assume that the probability distribution of the host, $M_a$, at accretion redshift $z_a$ follows a log-normal distribution with logarithmic mean value of $\overline{M}_a = M(z_a)$ [Eq. (4.8)], and logarithmic dispersion $\sigma_{\log M_a} = 0.12 - 0.15 \log(M_a/M_0)$. Following Yang et al. (2011), $F$ is defined as

$$F(s_a, \delta_a|S_0, \delta_0; \overline{M}_a) = \int \Phi(s_a, \delta_a|S_0, \delta_0; \overline{M}_a) P(M_a|S_0, \delta_0) dM_a, \quad (4.11)$$

where

$$\Phi(s_a, \delta_a|S_0, \delta_0; \overline{M}_a) = \left[\int_{S(m_{\text{max}})}^\infty F(s_a, \delta_a|S_0, \delta_0; M_a) \right]^{-1} \times \left\{ \begin{array}{ll} F(s_a, \delta_a|S_0, \delta_0; M_a), & \text{if } m_a \leq m_{\text{max}}, \\ 0, & \text{otherwise,} \end{array} \right. \quad (4.12)$$
\[ F(s_a, \delta_a|S_0, \delta_0; M_a) d\ln \delta_a = \frac{1}{\sqrt{2\pi}} \frac{\delta_a - \delta_M}{(s_a - S_M)^{3/2}} \exp \left[ -\frac{(\delta_a - \delta_M)^2}{2(s_a - S_M)} \right], \quad (4.13) \]

where \( m \leq m_{\text{max}} \equiv \min[M_a, M_0/2] \) as the subhalos accreting onto the main branch of its merger tree, and \((S_M, \delta_M)\) are defined at redshift value for which \( M = M_{\text{max}} = \min[M_a + m_{\text{max}}, M_0] \), as the main branch will increase its mass due to accretion of \( m_a \).

### 4.7.3 Mass-loss rate

We adopt a toy model to describe the subhalo mass loss following Jiang & van den Bosch (2016); Hiroshima et al. (2018a), in which all mass is assumed to be lost during the first orbital period within the host halo, in order to find the parameters for \( A \) and \( \zeta \) of Eq. 5. By Monte Carlo method, we obtain the mass-loss rate by considering host masses in the range \( M = [10^{-6}, 10^{16}] M_\odot \) and redshift range \( z = [0, 7] \), and fit the values of \( A \) and \( \zeta \). We find the following fitting functions,

\[
\log A = \left[ -0.0019\log \left( \frac{M(z)}{M_\odot} \right) + 0.045 \right] z + 0.0097\log \left( \frac{M(z)}{M_\odot} \right) - 0.31, \quad (4.14)
\]

\[
\zeta = \left[ -0.000056\log \left( \frac{M(z)}{M_\odot} \right) + 0.0014 \right] z + 0.00033\log \left( \frac{M(z)}{M_\odot} \right) - 0.0081. \quad (4.15)
\]

Reference (Hiroshima et al. 2018a) find slightly different fitting functions in the case of CDM. In both cases, however, \( A \) and \( \zeta \) only weakly depend on the host mass and redshift.

### 4.7.4 Subhalo structure before and after tidal stripping

We assume that the subhalos follow a NFW profile with a sharp drop at the truncation radius \( r_t \) as follows,

\[
\rho(r) = \begin{cases} 
\rho_s r_s^3 \left[ \frac{r}{r_s} \right]^{-2}, & \text{for } r \leq r_t, \\
0, & \text{for } r > r_t,
\end{cases} \quad (4.16)
\]

where \( r_s \) is the scale radius and \( \rho_s \) the characteristic density which is obtained as

\[
\rho_s = \frac{m}{4\pi r_s^3 f(c_{\text{vir}})}, \quad (4.17)
\]

with \( f(c) = \ln(1+c) - c/(1+c) \) and \( c_{\text{vir}} = r_{\text{vir}}/r_s \) the virial concentration parameter. The parameters \( r_s \) and \( \rho_s \) are related to the maximum circular velocity, \( V_{\text{max}} \), and
the corresponding radius $r_{\text{max}}$ as follows,

\begin{align}
  r_s &= \frac{r_{\text{max}}}{2.163}, \\
  \rho_s &= \frac{4.625}{4\pi G} \left( \frac{V_{\text{max}}}{r_s} \right)^2.
\end{align}

(4.18)

The evolution of subhalos before and after tidal stripping is found in Refs. (Peña-rubia et al. 2010; Hiroshima et al. 2018a; Ando et al. 2019b) by relating the maximum circular velocity $V_{\text{max}}$ and corresponding radius $r_{\text{max}}$ at accretion redshift $z_a$ and at any later redshift $z_0$,

\begin{align}
  \frac{V_{\text{max},0}}{V_{\text{max},a}} &= 2^{0.4} (m_0/m_a)^{0.3} \left( 1 + \frac{m_0}{m_a} \right)^{0.4}, \\
  \frac{r_{\text{max},0}}{r_{\text{max},a}} &= 2^{-0.3} (m_0/m_a)^{0.4} \left( 1 + \frac{m_0}{m_a} \right)^{-0.3},
\end{align}

(4.19)

where $m_0/m_a$ is the mass ratio between the subhalo after and before tidal stripping.

The truncation radius can then be found by relating $r_{\text{max}}$ and $V_{\text{max}}$ to the scale radius $r_s$ and characteristic density $\rho_s$ for the NFW profile. Using these relations, the subhalo mass after tidal stripping can be obtained by solving

\begin{equation}
  m_0 = 4\pi \rho_{s,0} r_{s,0}^3 f \left( \frac{r_{t,0}}{r_{s,0}} \right).
\end{equation}

(4.20)

We assume that subhalos with ratios $r_{t,0}/r_{s,0} < 0.77$ do not survive due to tidal disruption and remove them from further calculations (Hayashi et al. 2003).

### 4.7.5 Mass-concentration-redshift relation

The concentration of dark matter halos depends on their MAH, and, as WDM halos form later than CDM halos, they are expected to have a lower concentration due to a lower background density at later time. In particular, the concentration in the WDM case peaks at a mass scale related to its truncation scale, in contrary to the CDM case that has monotonic relations between mass, concentration and redshift. We adopt the mean concentration-mass-redshift relation, $\bar{c}_a(m_a, z_a)$ obtained in Ludlow et al. (2016), which is inferred from the MAH and can be applied to any WDM model. The concentration parameter $c_a$ is then drawn by following the log-normal distribution $P(c_a|m_a, z_a)$ around this mean $\bar{c}_a$. 

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Summary

All the objects we see around us are composed of elementary particles that interact, combine and form atoms, *matter*. Matter comprises from the smallest structures, such as the Hydrogen atom ($\sim 10^{-8}$ cm), to the largest structures in the Universe, such as galaxy clusters that consists of thousands of galaxies bound together by gravity ($\sim 10^{25}$ cm). Elementary particles, together with the fundamental interactions (gravity, electromagnetic, weak and strong) are well established by theory and experiments, and are described in the Standard Model. This is however not the complete story.

Various observations find missing mass which constitutes about 85% of the total matter in the Universe. It implies that we only understand 15% of the matter in the Universe and the rest is unknown matter; we call it *dark matter*. Observational evidence for dark matter is based on gravitational observations. The first hint of missing mass was found through the orbital motion of stars within galaxies. Stars that orbit the galactic center at large radii are observed to have such large velocities that exceeds the escape velocity and are not gravitationally bound. The presence of invisible mass can keep these fast orbiting stars within the galaxy. Dark matter is not only well observed on galactic scales, but also on larger scales such as galaxy clusters through gravitational lensing experiments and on cosmological scales through anisotropy measurement in the cosmic microwave background.

One of the popular theories about the nature of dark matter is that it consists of a new particle that only weakly interacts with Standard Model particles, consequently challenging the search for dark matter. A direct detection is yet to be made, and it is important to search for dark matter in many possible ways, as well as to consider a wide range of possible dark matter candidates to increase the detection probability.

Dark matter can be searched for in laboratories either by *direct detection* in underground experiments, where a passing dark matter particle interacts with the nucleus inside the detector, or in *collider experiments*, where Standard Model particles collide and produce dark matter particles. Another method is by *indirect detection*. Dark matter particles possibly annihilate or decay, and thereby produce Standard Model particles that leave an imprint in the astrophysical sky. Around dark matter rich regions, detectors will collect these signals on top of the expected astrophysical flux. In order to unravel the nature of dark matter, information on the dark matter
annihilation cross-section and decay lifetime are essential.

In this thesis, I explore the Galactic dark matter halo to search for dark matter through indirect detection. Dark matter halos are thought to be formed in the early Universe through collapse in regions with large dark matter density. The gravitational potential of dark halos attracted gas that fell inside and eventually collapsed to form stars and galaxies. Throughout time, dark matter halos merged to form larger halos in an hierarchical order, resulting in large halos with smaller halos inside, known as subhalos. The Milky Way galaxy is thus embedded in a large dark matter halo with a higher density towards its center. Within the Galactic halos resides smaller subhalos that can potentially host a galaxy, referred to as a satellite galaxies. Figure A illustrates the Galactic dark matter halo (purple), the Milky Way in the center that consists of visible stars and a disk (mainly gas clouds and stars including the Sun), the subhalos (black) and satellite galaxies within subhalos. The Galactic halo provides an excellent region to perform indirect dark matter searches due to the large dark matter density.

Figure A: Illustration (not to scale) of the Galactic dark matter halo (purple) with the Milky Way in the center and surrounding subhalos (black) and satellite galaxies.

Chapter 2 discusses indirect dark matter searches using high-energy (from $\sim 100$ GeV up to PeV) neutrino data with current and future neutrino telescopes. Neutrinos are very light Standard Model particles that interact weakly with other particles. Astrophysical neutrinos have been detected for the first time only in 2012 by the IceCube detector. In order to detect these elusive neutrinos, it is necessary to build
huge detectors. Indeed, IceCube uses a cubic kilometer of Antarctic ice as detector, and future neutrino telescope KM3NeT uses a cubic kilometer of Mediterranean Sea. Neutrinos that are produced through dark matter decay or annihilation, are expected to originate from the Galactic halo where the dark matter density is the highest. We studied the spatial distribution of neutrinos in order to distinguish between an astrophysical and dark matter origin. We showed that a possible dark matter origin in the current high-energy neutrino data of IceCube can be robustly excluded or confirmed in the near future. Moreover, based on a non-detection of dark matter, we can exclude significant values for the lifetime and cross-section of dark matter with mass between TeV to PeV with both IceCube and KM3NeT.

Chapter 3 discusses indirect dark matter searches using upcoming photon data at keV energies (X-rays) with eROSITA, that is currently performing an all-sky X-ray survey. Sterile neutrinos and axion-like particles are hypothetical particles that can explain the dark matter in the Universe with a particle mass at keV-energy scale. Their decay leads to narrow X-ray line emission, that can be observed as a diffuse emission from the Galactic halo. By constructing mock sky-maps, we test the sensitivity to detect such particles. We find that a non-detection of a dark matter signal will result in a large exclusion region in the dark matter parameter space. This has an impact on the possible observed dark matter signal at 3.5 keV with X-ray satellites and on the observed excess in recoil events at the XENON1T detector, possibly originating from axion-like particles, as both these signals can be tested with eROSITA.

Finally, Chapter 4 discusses the satellite galaxies of the Milky Way in order to distinguish between cold and warm dark matter models. Warm dark matter particles have smaller mass (∼ keV-scales) than the standard cold dark matter particles (∼ GeV-scales), and they therefore move faster. Observations have found less satellite galaxies than expected when assuming cold dark matter. It is currently not clear whether this can be resolved with a better understanding of the interplay with baryonic matter, or, whether non-cold dark matter needs to be considered, such as warm dark matter. If dark matter consists of warm particles, their thermal velocities at early times are substantially large that they free-stream out of dense environments. This leads to a delay and suppression of the formation of dark matter halos and to changes in the internal structure of halos, and thus in a smaller number of subhalos and satellite galaxies in the Milky-Way. To test warm dark matter models, we developed a Semi-Analytical SubHalo Inference Modelling code, SASHIMI, that can rapidly estimate the number of subhalos in a large halo for a given dark matter model. SASHIMI is based on mathematical models and (semi)-analytical relations that describe the formation and evolution of dark matter halos and subhalos. By comparing the estimated number of Milky-Way satellite galaxies with the observed number of satellites, we set lower limits on the thermal dark matter mass at 4.4 keV. For the case of sterile neutrino, combined with X-ray indirect detection constraints, we can exclude sterile neutrino models with a mass below 20 keV. These results do
not depend on baryonic effects and offer robust constraints that leave little room for warm dark matter candidates.

In conclusion, I explored various ways to search for a dark matter signal. The X-ray and neutrino sky put and will put strong constraints on possible dark matter candidates such as sterile neutrinos, axion-like particles and thermal warm and cold dark matter. In particular, both the detection and the non-detection of a dark matter signal with current (IceCube) and future (eROSITA, KM3Net and IceCube-Gen2) instruments will be important to characterise the long debated properties of dark matter. Finally, the code SASHIMI that we developed to estimate the abundances of Milky Way satellites provides one of the strongest and most robust constraints on warm dark matter models. Independent of the current uncertainties on galaxy formation, warm dark matter is not favoured as the dominant dark matter candidate.
Samenvatting

Alle objecten die we om ons heen zien bestaan uit elementaire deeltjes die interageren, combineren en atomen vormen, materie. Materie bestaat uit de kleinste structuren, zoals het waterstof atoom (\( \sim 10^{-8} \) cm), tot aan de grootste structuren in het Universum, zoals sterrenstelsel clusters die duizenden sterrenstelsels omvatten en verbonden zijn door zwaartekracht (\( \sim 10^{25} \) cm). Elementaire deeltjes en de fundamentele krachten (zwaartekracht, elektromagnetische kracht, sterke en zwakke kernkracht) zijn gegrondvest dankzij theoretische en experimentele onderzoeken, en worden beschreven in het Standaardmodel van deeltjesfysica. Dit is echter niet het complete verhaal.

Menigvuldige observaties vinden ontbrekende massa. Gebaseerd op deze observaties, ontbreekt maar liefst 85% van de totale massa in het Universum. Dat impliceert dat we enkel 15% van de totale massa in het Universum begrijpen en de rest onbekende materie is, genaamd donkere materie. Observationeel bewijs voor donkere materie is gebaseerd op zwaartekracht observaties. De eerste hint van ontbrekende massa werd gevonden in de jaren ’30 in de beweging van sterren in sterrenstelsels. Sterren die met een grote straal rondom het galactisch centrum bewegen, hebben zo een grote snelheid dat het de ontsnappingsnauwkeurigheid overschrijdt en ze niet gebonden kunnen zijn met zwaartekracht. De aanwezigheid van onzichtbare massa kan deze snel bewegende sterren in het sterrenstelsel houden. Donkere materie wordt niet enkel waargenomen op galactische schaal, maar ook op grotere schalen zoals in sterrenstelsel clusters met behulp van gravitatielenzen, en op kosmologische schaal met behulp van de temperatuurverschillen in de kosmische achtergrondstraling.

Een van de populaire theorieën over de aard van donkere materie is dat het bestaat uit een nieuw deeltje dat enkel zwak interageert met deeltjes in het Standaardmodel, en zodoende de zoektocht naar donkere materie uitdaagt. Een directe detectie is nog niet gedaan, en het is belangrijk om donkere materie zowel te zoeken door verscheidene technieken, als het beschouwen van een grote scala aan mogelijkheden voor de aard van donkere materie om de kans op een detectie te vergroten.

Donkere materie kan worden gezocht in laboratoria door directe detectie in ondergrondse experimenten, waar een passierend donker materie deeltje interageert met een atoomkern in het experiment. Of door botsingsexperimenten, waar een Stan-
Samenvatting

daardmodel deeltjes botsten en donkere materie produceren. Een andere methode is door indirecte detectie. Donkere materie kan annihileren of vervallen en daarbij Standaardmodel deeltjes produceren die een afdruk achterlaten in de astrofysische ruimte. In gebieden met een hoge dichtheid van donkere materie, zullen detectoren deze signalen opvangen bovenop de signalen die we verwachten van bijvoorbeeld astrofysische bronnen. Om de aard van donkere materie te ontrafelen, is informatie over de werkzame doorsnede (de waarschijnlijkheid van de wisselwerking tussen de donkere materie deeltjes) en de levensduur essentieel.

In dit proefschrift, onderzoek ik de halo die bestaat uit donkere materie rondom de Melkweg door indirecte detectie. Donkere materie halos worden in het vroege Universum gevormd door het ineenstorten van regio’s met een grote donkere materie dichtheid. De zwaartekracht potentiaal van donkere materie halos trekt gas aan die naar binnen valt en tenslotte sterren en sterrenstelsels vormen. Donkere materie halos combineren met elkaar en vormen grotere halos in een hiërarchische volgorde, resulterend in grote halos met kleine halos binnenin, bekend als subhalos. De Melkweg ligt daarom in een donkere materie halo met een grotere dichtheid richting het centrum. In deze Galactische halo bevinden zich kleinere subhalos die elk mogelijk een sterrenstelsel bevatten, bekend als satellietsterrenstelsels. Figuur A illustreert de Galactisch donkere materie halo (paars), met daarin de Melkweg in het centrum met de zichtbare sterren en een schijf (voornamelijk gas wolken en sterren zoals de Zon), de subhalos (zwart) en satellietsterrenstelsel in bepaalde subhalos. De Galactische halo biedt een uitstekende plek voor indirecte detectie vanwege de hoge donkere materie dichtheid.

Hoofdstuk 2 bespreekt indirecte detectie met behulp van hoog energetische neutrino data (van ∼ 100 GeV tot PeV energie) met huidige en toekomstige neutrino detectoren. Neutrinos zijn zeer lichte Standaardmodel deeltjes die enkel zwak met andere deeltjes interageren. Astrofysische neutrinos zijn voor het eerst gedetecteerd in 2012 met de IceCube detector. Om deze ongrijpbare deeltjes te detecteren is het noodzakelijk enorme instrumenten te bouwen. Inderdaad, IceCube gebruikt een kubieke kilometer aan Antartisch ijs als detector, en neutrino detector KM3NeT gebruikt een kubieke kilometer water van de Middellandse Zee. Van een groot deel van de neutrinos die kunnen worden geproduceerd bij verval of annihilatie van donkere materie worden verwacht van het Galactisch halo te komen, waar de donkere materie dichtheid het grootst is. We bestuderen de ruimtelijke verdeling van neutrinos om onderscheid te maken tussen neutrinos die van een astrofysische bron of van donkere materie komen. We laten zien dat een mogelijke donkere materie oorsprong met bepaalde eigenschappen significant kan worden uitgesloten in de huidige hoogenergetische neutrino data van IceCube. Bovendien, op basis van een non-detectie van donkere materie in de toekomst met IceCube en KM3NeT, kunnen we waardes van de levensduur of werkzame doorsnede significant uitsluiten met een donkere materie deeltje met massa tussen de TeV en PeV.
Hoofdstuk 3 bespreekt indirecte detectie met behulp van foton data in het keV bereik (röntgenstraling) met eROSITA, een telescoop die röntgenstraling meet vanuit alle richtingen van de hemel en zo een hemelkaart maakt. Steriele neutrino’s en axion-achtige deeltjes zijn hypothetische deeltjes die mogelijk het donkere materie in het Universum kunnen uitleggen en een massa kunnen hebben op keV-energie schaal. Hun verval leidt tot een emissie die zichtbaar is als een nauwe röntgenstraling lijn, die observeerbaar is als een diffuse emissie vanuit het Galactisch halo. Door middel van het reconstrueren van de hemelkaart met donkere materie emissie, testen we of eROSITA donkere materie kan meten. We vinden dat een non-detectie van een donkere materie signaal zal resulteren in een uitsluiting van belangrijke parameters van de donkere materie eigenschappen. Dit zal invloed hebben op zowel de mogelijk geobserveerde donkere materie signaal op 3.5 keV, gedetecteerd met röntgenstraling satellieten, en op een geobserveerd overmaat van detecties in de XENON1T detector, mogelijk afkomstig van een axion-achtig deeltje, aangezien beide kunnen worden getest met eROSITA.

Tenslotte bespreekt Hoofdstuk 4 de satelliet sterrenstelsels van de Melkweg om onderscheid te maken tussen koude en warme donkere materie modellen. Warme donkere materie deeltjes hebben een lagere massa (≈ keV-schaal) dan de standaard koude donkere materie deeltjes (≈ GeV-schaal), en ze bewegen daarom sneller. Observaties hebben minder satelliet sterrenstelsels gevonden dan verwacht bij een veronderstelling

**Figuur A:** Illustratie (niet op schaal) van de Galactische donkere materie halo (paars) met de Melkweg in het centrum en omringd door subhalos (zwart) en satellietsterrenstelsel.
van koude donkere materie. Het is momenteel niet duidelijk of dit kan worden opgelost met een beter begrip van de wisselwerking tussen donkere en standaard materie, of dat een niet-koud donkere materie nodig is, zoals warme deeltjes. Als donkere materie inderdaad bestaat uit warme deeltjes, is hun thermische snelheid zo hoog dat ze door gebieden met een hoge dichtheid propageren zonder te interacteren. Dit leidt tot een vertraging en suppressie van de formatie van donkere materie halos, en zal de interne structuur van halos veranderen. Zodoende zullen er een kleiner aantal subhalos en satelliet sterrenstelsels in the Melkweg zijn. Om warme donkere materie modellen te testen, ontwikkelen we een semi-analytisch subhalo code, SASHIMI, die het aantal subhalos in een grotere halo kan berekenen voor een bepaald donkere materie model. SASHIMI is gebaseerd op mathematische modellen en (semi)-analytische relaties die de formatie en evolutie van donkere materie halos en subhalos beschrijven. Door middel van het verwacht aantal Melkweg satelliet sterrenstelsels te vergelijken met het geobserveerd aantal satellieten, vinden we dat warme donkere materie geen massa kan hebben die kleiner is dan 4.4 keV. Steriele neutrinos kunnen een subgroep zijn van warme donkere materie. Onze resultaten met SASHIMI toegepast op steriele neutrinos, gecombineerd met resultaten van indirecte detectie met röntgenstraling, leiden tot uitsluiting van steriele neutrinos met massa’s kleiner dan 20 keV. Deze resultaten zijn niet afhankelijk van onzekerheden in de wisselwerking met standaard materie, en de resultaten zijn daarom robuust en laten weinig ruimte over voor warme donkere materie kandidaten.

Concluderend, heb ik verschillende methodes bestudeerd met als doel de eigenschappen van donkere materie beter te begrijpen. De hemelkaarten met röntgenstraling en neutrinos zetten momenteel en in de toekomst sterke limieten op mogelijke donkere materie kandidaten, zoals steriele neutrinos, axion-achtige deeltjes, en warme en koude donkere materie. Zowel een detectie als een non-detectie van een donkere materie met huidige (IceCube) en toekomstige (eROSITA, KM3NeT en IceCube-Gen2) instrumenten, zullen belangrijk zijn voor het karakteriseren van de lang besproken eigendommen van donkere materie. Tenslotte, de code SASHIMI die we hebben ontwikkeld voor het berekenen van het aantal satelliet sterrenstelsels in de Melkweg, plaatst een van de sterkste en robuuste limieten op warme donkere materie modellen. Onafhankelijk van de huidige onzekerheden in de formatie van sterrenstelsels, is warme donkere materie waarschijnlijk niet dominant als donkere materie kandidaat.
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Tous les objets que nous voyons autour de nous sont constitués de particules élémentaires qui interagissent entre elles, se combinent et forment des atomes, ce que nous appelons la matière. La matière est constituée depuis les plus petites structures, telles que l’atome d’hydrogène ($\sim 10^{-8}$ cm), jusqu’aux plus grandes structures de l’Univers, telles que les amas de galaxies qui contiennent des milliers de galaxies liées entre elles par gravité ($\sim 10^{25}$ cm). Les particules élémentaires et les forces fondamentales (gravité, force électromagnétique, force nucléaire forte et faible) ont été établies par des études théoriques et des recherches expérimentales, décrites dans le modèle standard de la physique des particules. Cependant, l’histoire n’est pas complète.

Des observations multiples ont révélé une masse manquante. Jusqu’à 85% de la masse totale de l’Univers est manquante. Cela implique que nous ne comprenons que 15% de la masse totale de l’Univers ; le reste est de la matière inconnue, appelée matière noire. Les preuves de l’existence de la matière noire reposent sur des observations de la gravité. Le premier indice de la masse manquante a été découvert dans les années 30 avec le mouvement des étoiles dans les galaxies. Les étoiles qui tournent à une grande distance de le centre galactique ont une vitesse telle que celle-ci dépasse la vitesse de fuite ; ces étoiles ne devraient plus être soumises à la gravité. La présence d’une masse invisible peut faire en sorte que ces étoiles qui se déplacent à grande vitesse soient maintenues dans leur galaxie. La matière noire n’est pas seulement observée à l’échelle des galaxies, mais aussi à des échelles plus grandes comme dans les amas de galaxies en utilisant des lentilles gravitationnelles, et à l’échelle cosmologique en utilisant les différences de température du fond diffus cosmologique.

L’une des théories les plus répandues sur la nature de la matière noire est qu’elle est constituée d’une nouvelle particule qui n’interagirait que faiblement avec les particules du modèle standard, et qui met au défi la recherche de la matière noire. Une détection directe n’a pas encore été faite ; c’est pourquoi il est important de rechercher la matière noire en utilisant toutes sortes de techniques et d’envisager un large éventail de possibilités quant à la nature de la matière noire afin d’augmenter les chances de sa détection.

La matière noire peut être recherchée en laboratoire par détection directe lors d’expériences sur terre dans lesquelles une particule de matière noire interagirait avec
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un noyau atomique. Ou par des expériences de collision, pendant lesquelles une particule du modèle standard entrerait en collision avec une autre particule et produirait de la matière noire. Une autre méthode est la détection indirecte. La matière noire pourrait s’annihiler ou se désintégrer, produisant des particules du modèle standard laissant ainsi une empreinte dans l’espace astrophysique. Dans les zones de forte densité en matière noire, les détecteurs devraient capter d’autres signaux, en plus des signaux que nous nous attendons à recevoir à partir de sources astrophysiques. Afin d’élucider la nature de la matière noire, il est essentiel de connaître la section efficace (la probabilité d’une interaction entre des particules de matière noire) et la durée de vie de ces particules.

Dans cette thèse, j’étudie le halo composé de matière noire autour de la Voie lactée par détection indirecte. Des halos de matière noire se sont formés à la suite de l’effondrement de régions à forte densité de matière noire, tôt dans l’Univers. Le potentiel gravitationnel des halos de matière noire attire du gaz qui y tombe pour finalement former des étoiles et des galaxies. Les halos de matière noire se combinent entre eux et forment des halos plus grands dans un ordre hiérarchique, ce qui donne de grands halos avec de petits des halos à l’intérieur, appelés sous-halos. La Voie lactée se trouve donc dans un halo de matière noire avec une plus grande densité vers le centre. Dans ce Halo galactique, il y a des sous-halos plus petits, chacun pouvant contenir une galaxie, connus sous le nom de galaxies satellites. La figure A illustre le halo galactique de matière noire (violet), avec au centre la Voie lactée composée d’étoiles visibles et d’un disque (principalement des nuages de gaz et d’étoiles comme le Soleil), les sous-halos (noir) et les galaxies satellites dans certains sous-halos. Le Halo galactique constitue un excellent endroit pour la détection indirecte en raison de la forte densité de matière noire. Figure A : Illustration (pas à l’échelle) du halo de matière noire galactique (violet) avec la Voie lactée au centre et entourée de sous-halos (noir) et de galaxies satellites.

Le chapitre 2 traite de la détection indirecte à l’aide de données sur les neutrinos de haute énergie (de ~ 100 GeV à l’énergie PeV) avec des détecteurs de neutrinos actuels et futurs. Les neutrinos sont des particules très légères du modèle standard qui n’interagissent que faiblement avec d’autres particules. Les neutrinos astrophysiques ont été détectés pour la première fois en 2012 avec le détecteur IceCube. Pour détecter ces particules insaisissables, il est nécessaire de construire d’énormes instruments. IceCube utilise d’ailleurs un kilomètre cube de glace de l’Antarctique comme détecteur, et le détecteur de neutrinos KM3NeT utilise un kilomètre cube d’eau de la mer Méditerranée. Une grande partie des neutrinos qui seraient produits par désintégration ou annihilation de la matière noire proviendrait du halo galactique, là où la densité de matière noire est la plus élevée. Nous étudions la distribution spatiale des neutrinos pour distinguer les neutrinos qui proviennent d’une source astrophysique et ceux produits par la matière noire. Nous démontrons que l’hypothèse de l’origine possible de ces neutrinos par la matière noire, dans les données actuelles des neutrinos
à haute énergie de IceCube, peut être significativement exclue. En outre, sur la base d’une non-détection de la matière noire dans le futur avec IceCube et KM3NeT, nous pourrions exclure de manière significative les propriétés de durée de vie ou de section efficace pour une particule de matière noire dont la masse est comprise entre le TeV et le PeV. Le chapitre 3 traite de la détection indirecte à l’aide de données sur les photons dans la gamme des keV (rayons X) avec eROSITA, un télescope qui mesure les rayons X provenant de toutes les directions du ciel et crée ainsi une carte du ciel. Les neutrinos stériles et les particules de type axion sont des particules hypothétiques qui pourraient expliquer la présence de matière noire dans l’Univers et pourraient avoir une masse sur une échelle d’énergie de l’ordre du keV. Leur désintégration conduit à une émission qui est visible comme une ligne étroite de rayons X, qui est observable comme une émission diffuse du halo galactique. En reconstruisant la carte du ciel avec des émissions de matière noire nous testons si eROSITA peut mesurer la matière noire. Nous constatons qu’une non-détection de signal de matière noire entraînerait l’exclusion de paramètres importants liés aux propriétés de la matière noire. Cela affecterait l’interprétation du signal de matière noire observé à 3,5 keV, détecté avec des satellites rayons X, mais aussi de l’excès de détections observé dans le détecteur XENON1T, pouvant provenir d’une particule de type axion, sachant que ces deux détections peuvent être testées avec eROSITA.

Enfin, le chapitre 4 traite des galaxies satellites de la Voie lactée afin de distinguer
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les modèles de matière noire froide et chaude. Les particules de matière noire chaude ont une masse plus faible (échelle keV) que celles de la matière noire froide standard (échelle \(\sim \) GeV), et elles se déplacent donc plus rapidement. Les observations ont montré que les galaxies satellites sont moins nombreuses que prévu dans l’hypothèse d’une matière noire froide. Il n’est pas clair, à l’heure actuelle, si ce problème peut être résolu grâce à une meilleure compréhension des échanges entre matière noire et matière standard, ou qu’une matière noire non froide est nécessaire, comme des particules chaudes. Si la matière noire est effectivement composée de particules chaudes, leur vitesse thermique est si élevée qu’elles se propageraient dans les zones à forte densité sans interagir. Cela conduirait à un ralentissement et à une suppression de la formation de halos de matière noire, et modifierait la structure interne des halos. En conséquence, il y aurait un certain nombre de sous-halos et de galaxies satellites dans la Voie lactée. Pour tester le modèle de matière noire chaude nous développons un code semi-analytique pour les sous-halos, SASHIMI, qui peut calculer le nombre de sous-halos dans un halo plus grand pour un modèle de matière noire donné. SASHIMI est basé sur des modèles mathématiques et des relations (semi-)analytiques qui décrivent la formation et l’évolution des halos et sous-halos de matière noire. En comparant le nombre calculé de galaxies satellites de la Voie lactée avec le nombre observé, nous trouvons que la matière noire chaude ne peut pas avoir une masse inférieure à 4,4 keV. Dans l’hypothèse que les neutrinos stériles feraient partie des particules de matière noire chaude, nos résultats du modèle SASHIMI combinés avec les résultats de l’étude de détection indirecte par rayon X, permettent d’exclure les neutrinos stériles dont la masse serait inférieure à 20 keV. Ces résultats ne dépendent pas des incertitudes liées à l’interaction avec matière standard, c’est pourquoi ces résultats sont robustes et laissent peu de place à l’incertitude.

En conclusion, j’ai étudié différentes méthodes dans le but de mieux comprendre les propriétés de la matière noire. Les cartes du ciel avec les rayonnements X et les neutrinos imposent actuellement et à l’avenir de fortes limites aux candidats possibles à la matière noire, comme les neutrinos stériles, les particules de type axion, et la matière noire chaude et froide. La détection autant que la non-détection de la matière noire avec les instruments actuels (IceCube) et à venir (eROSITA, KM3NeT et IceCube-Gen2), seront importantes pour spécifier les propriétés de la matière noire dont on parle depuis longtemps. Enfin, SASHIMI que nous avons développé pour calculer le nombre de galaxies satellites de la Voie lactée, place l’une des limites les plus fortes et les plus robustes sur les modèles de la matière noire chaude. Indépendamment des incertitudes actuelles sur la formation des galaxies, nous pouvons exclure l’hypothèse que la matière noire chaude soit matière noire dominante.
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Figure B: Ariane and Shin’ichiro in front of the poster at the Neutrino 2020 conference.